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SUMMARY

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Letter from the Editor

Welcome to the sixth edition of Acoustics in Practice. The journal has suffered several changes during the last year, from the Editor in Chief to the Editorial Board. Now we have renewed the board with several experts trying to cover all areas of acoustics, but also represent as many as possible of the EAA member societies. The Journal is reborn stronger and with new goals that will be tackled shortly as: trying to get indexed, publishing articles individually and independent of the journal, exploring new ways of web publishing and much more.

The journal serves the many practitioners members of the European Acoustics Association's member societies who work in the many areas of applied acoustics including consultancy, policy making, regulation and manufacturing.

This number has been completed with 7 very interesting articles and diverse topics, covering aspects of environmental acoustics such as *Improving assessment of noise impact* or an *overview of recent developments with regards to the Environmental Noise Directive. W*ith respect to transport noise, *an empirical method for prediction of tram noise* and an a*ssessment of warning sound detection for electric vehicles* are discussed.

This issue also includes an interesting review of *the use of Modern shows in Roman amphitheatres* and a very technical article that includes a list of *sound scattering coefficients for structures having uneven surfaces found in industrial work places.*

A separate mention should be made of the *Relevance of acoustic Performance in Green Building Labels and Social Sustainability Ratings*.

One of our journal's objectives has been to disseminate knowledge and experience gained in our member countries across the entire European membership. All too often authors present their findings at local and national conferences and these papers are not accessible to members in other countries. We encourage these authors to publish their work in Acoustics in Practice to gain a Europe-wide and permanent web presence for their work.

The publishing team, the authors and the entire Editorial Board wants you to enjoy the magazine and encourages you to publish your works in order to broadcast it among all the Acoustic Societies of Europe and gain greater visibility.

Miguel Ausejo
(AiP Editor in Chief)

Counting houses: Improving assessment of noise impact using the Design Manual for Roads and Bridges

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ABSTRACT

Noise mapping software has greatly simplified the accurate and rapid calculation of noise levels arising from infrastructure projects, but techniques for assessing and presenting noise impact have lagged behind and indeed have changed very little in the last 40 years. The UK guidance on assessing the noise impact of trunk road schemes is set out in the *Design Manual for Road and Bridges*. An assignment set for Institute of Acoustics students in 2014, using the DMRB to assess a simple road scheme, proved to be a "test of character" according to tutors: few students obtained the expected answer. The noise assessment process has become more complex rather than better over the years, and manual application of the process has become impracticable.

This paper briefly describes computerised methods of applying the DMRB procedures that avoid the pitfalls of manual methods of "counting houses" and describes recent advances that allow this to be done directly within noise mapping software, rather than post-processing in GIS or spreadsheet systems. It concludes that this development provides the tools needed for the practicable development of new and better methods of noise impact assessment.

1. INTRODUCTION

Noise mapping software has greatly simplified the accurate calculation of noise levels arising from infrastructure projects, such as roads and railways. However, in practical terms, this is of limited benefit unless the noise impact of such projects can be assessed and presented with similar accuracy, speed and accessibility. This noise impact needs to be understandable not only to technical teams but also to the general public and other stakeholders involved in the design, assessment and planning process.

Unfortunately, techniques for assessing and presenting noise impact have lagged behind developments in noise calculation, and indeed have changed very little in the last 40 years. Even in 1974, hand-drawn maps (Figure 1) and tables were being prepared to show changes of noise level and facades qualifying for noise insulation under the then-new Noise Insulation Regulations 1973 [1] (superseded by the 1975 Regulations [2] and later revisions).

This paper considers why methods of noise impact assessment have lagged so far behind noise mapping and shows ways in which this could be improved.

2. PRESENT UK APPROACH TO NOISE IMPACT ASSESSMENT

2.1. Methods of noise impact assessment

Various UK and EU governmental agencies have published guidance on noise impact assessment. There are four main approaches, which can be broadly summarized as follows:

i) assessing the (change in) noise level at noise-sensitive receivers (NSRs);

ii) assessing the (change in) noise annoyance (dissatisfaction, bother, nuisance) at NSRs;

iii) assessing future noise levels against absolute criteria;

iv) assessing the monetary value of the (change of) noise level at NSRs.

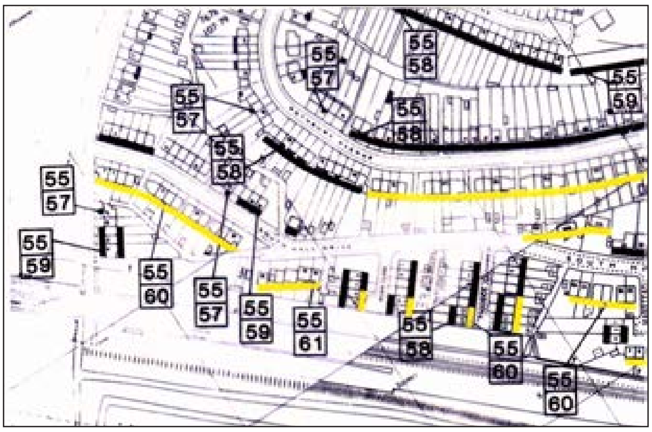

Figure 1. Part of Hand-drawn Noise Map, 1989.

2.2. DMRB Methodology

In the UK, perhaps the most important guidance on assessing the impact of road schemes is that set out in the Highways Agency's *Design Manual for Roads and Bridges*. Volume 11, Section 3, Part 7 contains guidance on the assessment of Noise and Vibration [3]. This was first published in 1992 and has been regularly revised, with the latest version being dated November 2011. It contains around 30 pages of detailed instructions on reporting the noise impact of (trunk) road schemes, but it shies away from advising on how to rank options in order of preference.

2.3. Experience with DMRB

Despite the extensive and detailed guidance, the DMRB procedures for assessing noise impact are difficult to apply, even in simple cases. A hypothetical example was presented as an assignment to 62 IoA Diploma Students in May 2014. It considers a street with two rows of ten terraced houses, one row each side of a busy and congested road, see Figure 2. Two options were presented for relieving the congestion of this road: one was to widen the existing road and the other was to build a bypass behind one of the existing rows of housing.

The students were provided with Do-minimum and Do-something noise levels for the baseline year. Their task was work out the changes of noise level and changes of noise "nuisanc"' in accordance with the DMRB procedures; to count up the number of properties in each category of change; and to present the results in the standard DMRB assessment tables. They were also asked to provide an opinion as to which option had the least noise impact. Despite its simple appearance, very few students got the expected answer, and opinion was fairly evenly divided over

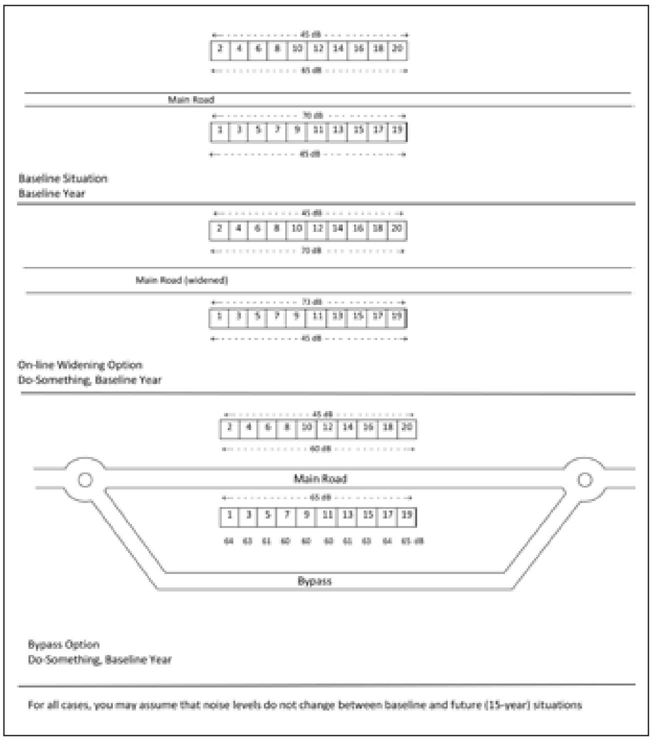

Figure 2. Assignment for Students to assess noise impact.

whether the by-pass or the on-line widening had the least noise impact. Although this should have been an easy assignment, students found the opposite, with one tutor reporting that completing the assignment was "a test of character"!

2.4. Difficulties with DMRB

The DMRB must take some of the responsibility for the students' difficulties: its advice is not set out as a procedure to be followed in a straightforward sequence, but instead it is spread over 30 pages of densely argued reasoning and instructions which need effort and practice to absorb.

Moreover, some of the advice lacks clarity. One major problem for students was what do when the change of noise level is different on the front and rear facades of a property, a common occurrence. DMRB instructs users to make the assessment for the façade with the "least beneficial change". However, its terminology caused many students to understand that where one façade had no change in noise level, but the other had a reduction, taking the least beneficial change meant that they disregarded the reduction in noise and they recorded "no change".

Calculating the change of noise nuisance was a challenge, as the procedure usually rates cases of increase in noise annoyance from the short-term impact, whilst cases of reduction in noise annoyance are usually rated from the much lower long-term impact. These use different charts or formulae, and care is needed to ensure the right ones are used.

3. THE PROFESSIONAL APPROACH

3.1. Assessment from noise maps

Most real projects are much more complex than the above example. They can involve thousands of building facades with complex changes in noise level, where computerized assistance is essential.

A method developed by the author's team at Atkins in 2003 for the London Road Traffic Noise Map [4] was to use GIS algorithms to overlay building outlines onto a noise map, see Figure 3, and thereby obtain the noise level on each façade. The London Road Traffic Noise Map required a count of the noise level on the most exposed (noisiest) façade, so once the façade noise levels were derived, this was straightforward to extract (Figure 4).

Obtaining *changes* of noise level is more complex because the exposure on each façade must be recorded for each scenario and the least beneficial change then extracted. This problem is solvable programmatically and an accurate result can be obtained. However, the work previously required GIS software, operated by specialists, which can be costly and slow.

However, it is no longer necessary to use an independent GIS system for this, as the work can now be done in noise mapping software.

3.2. Assessment using façade noise levels

Figure 5 shows a change of noise level map for a scheme which consists of building a new link road (running east-west in the figure), thereby relieving existing roads (running north-south in the figure).

The noise map makes it easy to visualize the noise changes that the scheme would bring about, although they are complex: blue and pale green colours indicate noise reduction, whilst darker green, yellow and red

Figure 3. *Noise contours overlaid.*

Figure 4. *Noise levels applied to buildings.*

Figure 5. *Noise Contour Map showing change of noise levels on part of larger scheme.*

colours indicate an increase in noise level. Many of the houses have different amounts of change on front and rear facades, with particular intricacy around the houses because of the screening they create. It is obvious that counting changes of noise level on this map would be a difficult task.

A better approach is to generate individual receptor points around each building façade. This can be done automatically using NoiseMap five software [5] and the address of each receiver point can be extracted from the AddressPoint (postcode) database. This contains the location and address of every occupiable residential or non-residential building in the UK, including information that can be used to determine the type of building. This means that residential buildings, schools, commercial and other buildings can be identified. Next, the noise level at each receiver point is calculated from the noise model. Calculations are made for each scenario, such as Do-minimum, Do-something, baseline year, and design year, see Figure 6 for an example.

Once the noise levels are available, it is a matter of identifying the scenarios to be assessed and software can then programmatically produce the DMRB assessment tables. This process can, in practice, be quicker than creating contour maps, as fewer calculation points are required. The approach can be readily extended to other types of impact assessment, such as eligibility for statutory noise insulation, changes of noise level for Part 1 Compensation [6] claims, and the monetary analysis required by TAG [7] , which is otherwise very difficult to do even though automated spreadsheets are available.

4. ASSESSMENT AND RATING OF NOISE IMPACT

4.1. Comments on the DMRB assessment tables

The DMRB sets out a variety of assessment tables that must be produced at the "detailed" assessment stage. These are set out in Tables 1 to 3 for the scheme of which Figure 5 is part. It may be noted that there are 9598 properties within the study area of that scheme and it is required to classify these in terms of the change of noise level both short-term and long term. It is also necessary to calculate the change of "nuisance" (bother) for traffic noise in terms of L_{A10} (18-hour) and L_{night} indexes, plus airborne vibration. The table showing change in traffic vibration nuisance is not reproduced here to save space.

These figures look rather alarming, with large numbers of properties affected, but having acquired all this data,

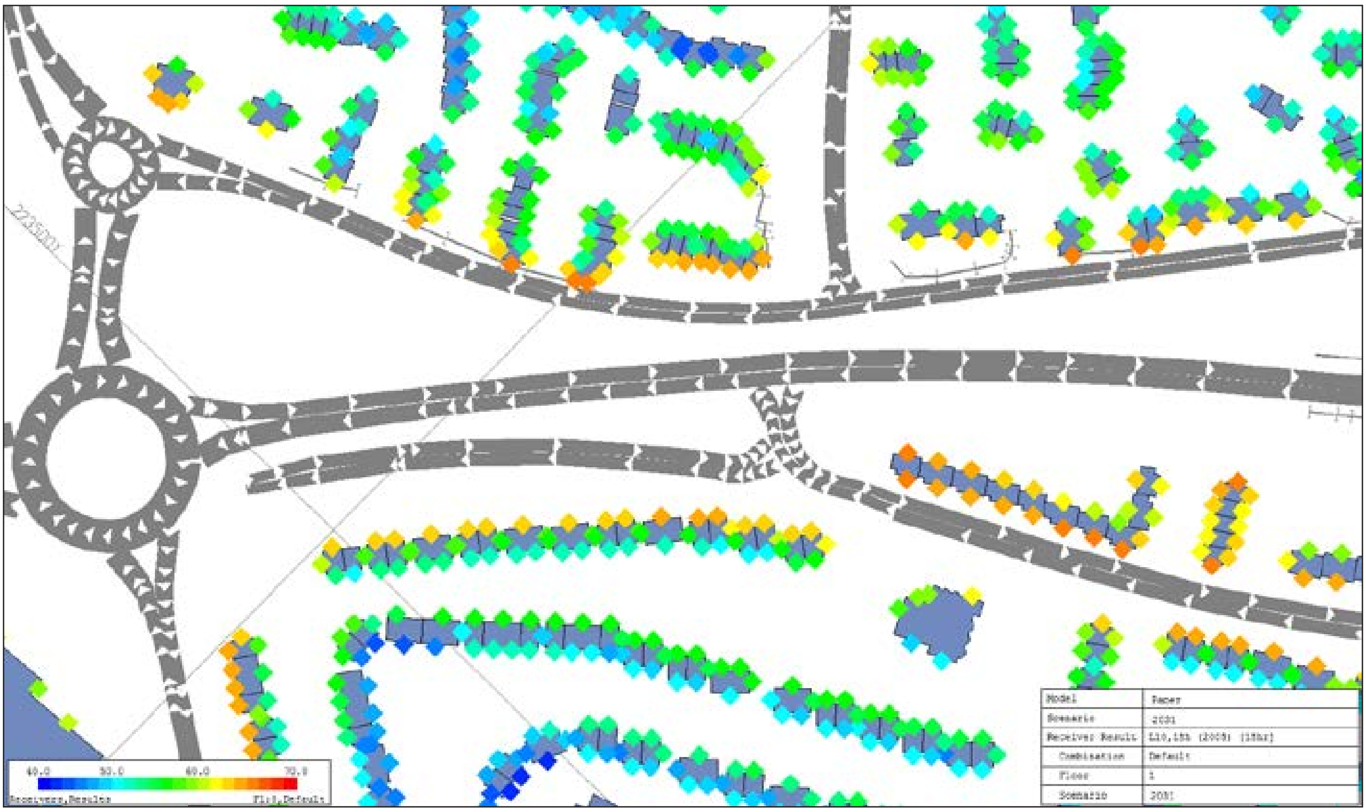

Figure 6. *Noise Map showing Receiver Noise Levels on same part of scheme.*

the DMRB does not suggest any method of assessing the overall impact of a scheme, stating that a methodology has not yet been developed.

The problems of using changes of noise level to rank schemes are well known. For example, whether a scheme that exposes a few properties to a large increase in noise is preferable to a scheme that exposes a large number of properties to a small increase in noise; and whether the importance of a change of level is the same regardless of the noise level of the starting point.

When DMRB introduced the assessment of change of “nuisance” (ie noise annoyance), this gave the possibility of ranking schemes according to the total number of people annoyed by noise in each of the options. This would have given a single number rating for each option. However, in the most recent edition of DMRB, this has been dropped in favour of a table showing “change in nuisance level”. This is not much different from the change of noise level table, except that the procedure usually rates increase in noise annoyance from the short-term impact, and the reduction in noise annoyance from the much lower long-term impact. This has the justifiable effect of heavily discounting reductions in annoyance resulting from noise reductions brought about by a scheme.

However, the term “nuisance level” adopted in the assessment tables is misleading: it is *not* a measure of the amount of annoyance experienced by any one person: it is a measure of the proportion of a typical *community* that will be “bothered quite a lot or very much” by the noise. Moreover, because the assessment table is phrased in terms of the change in percentage of people bothered, it falls into the same trap as the change of noise level table: the starting point of the annoyance is not reported. Thus it implicitly assumes that an increase of 40 % in annoyance has the same significance whether the increase is from a base of 1 % already bothered or 60 % already bothered.

4.2. Opportunities for improvement

Rather than noise impact assessment techniques improving over time, the situation has arguably worsened with a proliferation of new indexes, such as the L_{den} and L_{night}, which add confusion rather than clarification.

The EU’s Environmental Noise Directive (END) [8] had the potential to create a paradigm shift in noise impact assessment, as indeed it did create in noise mapping, but since then it seems to have faded into a

Table 1. Short-term Change in Traffic Noise Levels within Study Area.

Change in Noise Level Do-minimum v Scheme in opening year		Number of Dwellings	Number of other receptors
Increase in Noise Level, $L_{A10,18hr}$	0.1 - 0.9	926	
	1.0 - 2.9	3949	2 schools
	3.0 - 4.9	53	
	5 +	17	
No Change	0	79	
Decrease in Noise Level, $L_{A10,18hr}$	0.1 - 0.9	728	
	1.0 - 2.9	957	
	3.0 - 4.9	1182	
	5 +	1707	

Table 2. Long-term Change in Traffic Noise Levels within Study Area.

		Daytime		Night-time*
Change in Noise Level Do-minimum in Baseline year v Scheme in design year		Number of Properties	Number of other sensitive receptors	Number of dwellings
Increase in Noise Level, $L_{A10,18hr}$	0.1 - 2.9	5087	2 schools	–
	3.0 - 4.9	267	–	–
	5.0 - 9.9	30	–	–
	10 +	1	–	1
No Change	0	94	–	–
Decrease in Noise Level, $L_{A10,18hr}$	0.1 - 2.9	1533	–	–
	3.0 - 4.9	964	–	11
	5.0 - 9.9	1463	–	–
	10 +	159	–	–

Table 3. Change in Traffic Noise Nuisance within Study Area.

Between Baseline year and Design Year		Do-Minimum Number of Dwellings	Do-Something Number of Dwellings
Increase in Nuisance Level	< 10 %	9504	420
	10 < 20 %	0	506
	20 < 30 %	0	3114
	30 < 40 %	0	890
	> 40 %	0	15
No Change	0	94	79
	< 10 %	0	4574
Decrease in Nuisance Level	10 < 20 %	0	0
	20 < 30 %	0	0
	30 < 40 %	0	0
	> 40 %	0	0

Table 4. *Number of people bothered by noise.*

Total dwellings	Do minimum Baseline Year	Do something Baseline Year	Do something Future Year
9598	1552	1589	1682

bureaucratic process. As part of the work towards the END, the Day-Evening-Night (L_{den}) index was adopted as a universal measure of noise exposure. A committee of European experts put forward a series of dose-response relationships that relate noise annoyance to noise exposure measured in terms of the L_{den}, and they go so far as to recommend that the percentage of people annoyed [%A] should be used as the preferred descriptor of noise annoyance in a population. Furthermore, they suggest that noise criteria should be set in these terms.

This gives some backing to the earlier DMRB approach of calculating the total noise annoyance of each scheme option. Total annoyance has been evaluated for the example scheme and the results are shown in Table 4. It can be seen that despite the large number of properties in the study area, the number suffering noise annoyance is much more modest and changes by a relatively small amount as a result of the proposals. Annoyance could be used as a common factor in multi-modal analysis, and indeed the controversial monetary analysis attempted by TAG is actually based on annoyance percentages. TAG attempts to reduce all factors to monetary values so that cost-benefit analysis can be adopted.

As with any type of performance indicator, there needs to be post-construction validation, to ensure that attempts to improve methodology have had the desired effect. For example, the National Roads Authority of Ireland (NRA) undertook an extensive post-construction evaluation of a number of Environmental Impact Assessments, culminating in the consultation draft "Good Practice Guidance for the Treatment of Noise during the Planning of National Road Schemes" [9] (December 2013) in which the present author was involved. This advises on the practical implementation of the NRA's "Guidelines for the Treatment of Noise and Vibration in National Road Schemes" [10]. These Guidelines are based around an absolute noise level as a design goal, and the review showed that noise barriers were sometimes being used in potentially unsustainable ways to achieve this goal.

5. THE FUTURE

It is clear that present noise assessment procedures are recognizably the same as 40 years ago, but study areas have become much larger and more scenarios need to be considered. The proliferation of noise indexes and assessment tables has not led to better evaluation or understanding of noise impact, and there is inadequate guidance on how the plethora of information should be interpreted.

It is possible that one reason for the stagnation of noise impact assessment has been the difficulty of presenting results quickly and clearly. However, this paper shows that a new generation of noise assessment tools is available.

This gives a new generation of researchers the opportunity to take advantage of new tools and to apply them to improving this much-neglected area of work.

6. REFERENCES

[1] The Noise Insulation Regulations 1973. SI 1973/1363.

[2] The Noise Insulation Regulations 1975. SI 1975/1763.

[3] Design Manual for Roads and Bridges, Volume 11, Section 3, Part 7, Environmental Assessment Techniques - Noise and Vibration (Highways Agency, Nov. 2011).

[4] Noise Mapping London - Contract Completion Report. Ref:6742-E079 (Atkins 2004).

[5] NoiseMap five software - NoiseMap Ltd. Epsom, Surrey. www.noisemap.com

[6] Land Compensation Act 1973, Part One.

[7] Transport Analysis Guidance - TAG Unit A3 - Environmental Impact Appraisal (DoT 2014).

[8] The Assessment and Management of Environmental Noise. Directive 2002/49/EC.

[9] Good Practice Guidance for the Treatment of Noise during the Planning of National Road Schemes. Draft for Consultation, December 2013. National Roads Authority, Ireland.

[10] Guidelines for the Treatment of Noise and Vibration in National Road Schemes. October 2004. National Roads Authority, Ireland.

Modern shows in Roman amphitheatres

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ABSTRACT

Until now little attention has been paid to the acoustics of Roman amphitheatres compared to ancient Greek and Roman theatres. Although conceived for different purposes, nowadays also some Roman amphitheatres are used for various genres of public shows which in part could be appreciated better in appropriate theatres and auditoriums, e.g. drama, opera, classical, pop, rock and jazz music. The present paper describes the amphitheatres where events are organized with a certain seasonal continuity. Differences with respect to Roman theatres are highlighted. Some comments about their natural acoustics and their suitability for specific musical events are reported.

Keywords: Roman Amphitheatres, modern shows, opera, music shows

1. INTRODUCTION

Roman theatres and amphitheatres are a cultural heritage spread mostly in countries surrounding the Mediterranean Sea and other regions under the rule of the Roman Empire (27 BC- ≈ 395 AD). The remains of about 230 amphitheatres have been found. Their state of conservation is various. Some are in a good state, others are only traces of stone testifying their presence in the past. Nowadays some in a state of good preservation are used for public events more or less regularly. Besides a general archaeological and historical interests, more attention has been paid instead to ancient theatres during the last decades aiming at the increment of the knowledge about various characteristics of these theatres, their use, their valorisation and conservation. Many research results stemming from EU and national funded projects, e.g. [1, 2, 3, 4], have been published in project reports, scientific journals and congress proceedings including various aspects related to their acoustics. However, a lack of adequate studies about the acoustics of amphitheatres still persists. As shown in Figure 1, typical shapes of a Roman theatre and a Roman amphitheatre are different.

The different shape and dimensions of Roman amphitheatres compared to unroofed Roman theatres determine acoustic differences in the area occupied by the spectators. This is not surprising because the amphitheatres were designed to accommodate a lot of people seeing articulated actions moving in large arenas surrounded by spectators. The actions in a Roman theatre were usually confined into an area before the stage building. Spectators were arranged on semicircular ascending steps looking toward the stage. Amphitheatres did not need careful acoustics like that provided by the structures of Roman theatres. While amphitheatres had to host gladiatorial

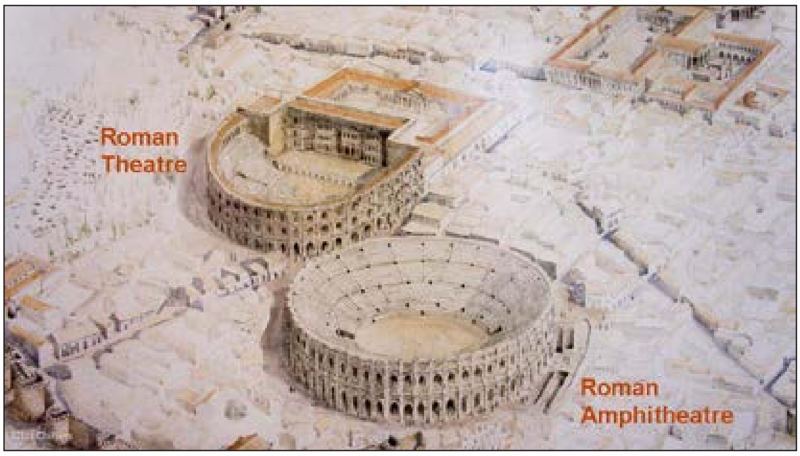

Figure 1. Typical shapes of a Roman theatre and a Roman amphitheatre (modified from [5]).

combats, races and other events mostly to be seen, theatres hosted events such as plays, pantomimes, choral events and orations not only to be seen but especially to be heard correctly. Today some Roman amphitheatres in their good state of conservation are known to host modern public performances in Italy and other countries. A brief recall of their nature and use for public shows is reported in the following.

2. AMPHITHEATRES HOSTING MODERN SHOWS

A relatively accurate screening of Roman amphitheatres where traditionally various kinds of public shows are hosted with a seasonal continuity, resulted in the selection of Verona Arena, Arena of Nîmes, Arena of Arles, Pula Arena and El Djem Arena.

2.1. Verona Arena (Verona, Italy) [6,7,8]

This is an astonishing Roman amphitheatre built in 30 AD. The Arena, as it stands today, is the result of the constant removal of materials, but also of an earthquake that struck Verona in the 12th century and other disastrous events that leaved indelible traces on the monument. Only four arches (called *Vela*) are left of the outer circle, which was the real façade. Among other Roman amphitheatres, this venue offers an intensive and rich production of modern public shows. Since 1913 the flagship of the arena is opera performance. In fact, the start of the tradition is dated on 10 August 1913 when Verdi's Aida was staged to celebrate the centenary of the birth of the famous composer of opera Giuseppe Verdi. Save the periods of the first and second world wars, an opera festival has been organized uninterruptedly with at least four different productions each year during summertime. Figure 2 displays an external view (left) and an internal view (right) of the Verona Arena as it stands today. The orchestra pit is opened when an opera is performed otherwise seats for spectators are arranged on the closure.

In more recent times, the arena has hosted several concerts of international rock and pop artists (e.g. Pink Floyd, Rod Stewart, Sting, Paul McCartney and many others). Jazz and ballet have been further performances offered to public in the arena (e.g. the jazz musician Keith Jarrett and the ballet dancer Roberto Bolle and Friends). It is worth mentioning that large symphonic orchestras and chorus have played on the stage of the arena (e.g. Ennio Morricone, a well known composer of musical sound tracks for movies and orchestra conductor). Figure 3 shows two different examples of set-ups of the arena. The left side is related to an opera (Verdi's Aida) and the right side refers to a pop/rock concert (Paul Mc Cartney).

Verona Arena receives continuous structural surveillance and maintenance. Information about the Verona Arena (history, books, videos and pictures) was obtained by browsing the www and selecting critically what is compacted above starting from references and links reported in [6,7,8].

2.2. Arena of Nîmes (Nîmes, France) [9,10,11]

This magnificent Roman amphitheatre was built at the end of the first century AD. After the fall of the Roman Empire, many troubled vicissitudes afflicted the arena. The dominations of Visigoths, Muslims, Franks and other rulers with their wars and conflicts caused the transformation of the amphitheatre into a fortification against dangerous assaults to the population. In the 13th century, after the region was incorporated into France, the arena became a gated community of about 700 people living in houses built inside the monument.


Figure 2. Verona Arena. An external view (left). An internal view (right). The orchestra pit is opened when an opera is performed.

Figure 3. Set-ups of the Verona Arena. Left: Opera performance (Verdi's Aida). Right: Pop/rock concert (Paul Mc Cartney).

Figure 4. Arena of Nîmes. An external view (left). An internal view (right).

In 1809, the added construction were demolished to give the monument its initial appearance. Only in 1863 this monument was remodelled and restored almost as it is in the actual state. Figure 4 shows an external view (left) and an internal view (right) of the Arena of Nîmes.

When demolitions of added constructions were completed, people begun to assist to activities that took place in the arena, e.g. first bullfights (1813), chariot races (1840), gym competitions (1850), bull brandings (1852), wrestlers, (1853), Spanish bullfight (1853), Bizet's Carmen with bullfight (1901), Sophocles' tragedy Oedipus the King (1903), Herold's Le jeune dieu with scenography (1911). Later, during the twentieth century up today, events in the Arena of Nîmes have been intensified and some have been organized as periodic festivals (*Ferias*). The arena is the site of two annual bullfights during the Feria of Pentecost (started in 1952) and the Feria of the Harvest. Furthermore, the representations of the Great Roman Games mimicking ancient events in ancient Roman amphitheatres are offered. During summertime the management of the annual Festival of Nimes, for the part held in the arena, organizes music concerts of various genres, theatre plays and ballets. Opera is offered to public nowadays and in the past (e.g. Aida, Turandot, Nabucco and others). Traditionally, a version of Bizet's Carmen is staged every year. From 1976 to 1988 the amphitheatre hosted the Nîmes International Jazz Festival, with the participation of legendary musicians, like Miles Davis, Charlie Mingus, Dizzy Gillespie, Michel Petrucciani, Sonny Rollins and others. During the Festival of Nimes pop and rock concerts are organized in the arena. Artists like Elton John, Phil Collins, Sting, Johnny Hallyday and many others have played in the amphitheatre. Figure 5 shows two different examples of set-ups of the arena. The left side is related to an opera (Puccini's Turandot) and the right side refers to a pop/rock concert (Elton John).

It is worth to report that between the late 1980s and early 2000s, the arena was covered with a removable translucent roof. It was an inflatable lens-like structure which enabled the holding of sports played indoors. In

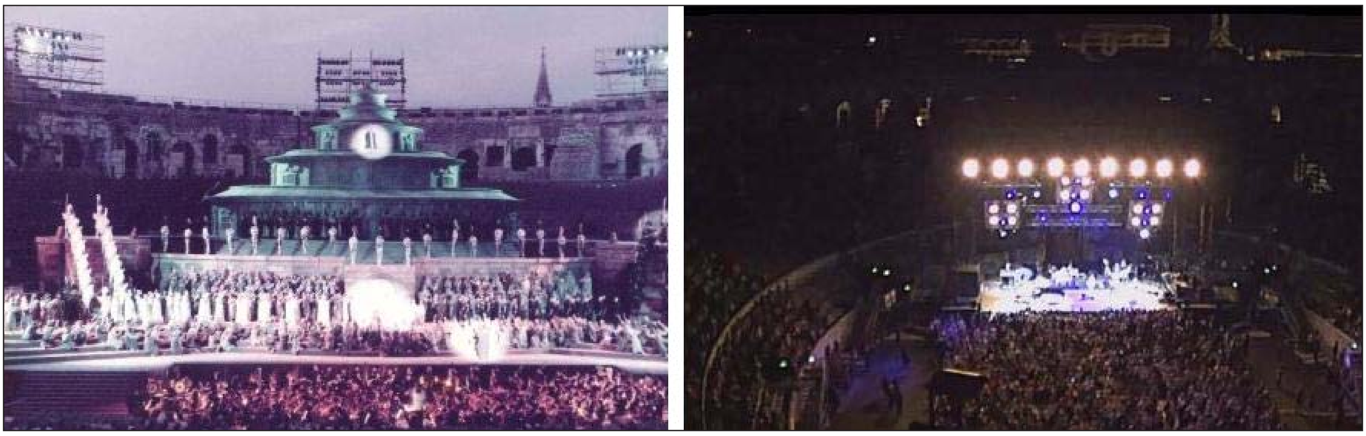

Figure 5. *Set-up of the Arena of Nîmes. Left: Opera performance (Puccini's Turandot); Right: Pop/rock concert (Elton John).*

Figure 6. *Arena of Arles. An external view (left) and an internal view (right).*

fact, the monument has served also in several sporting events. Arena of Nîmes receives continuous structural surveillance and maintenance. Information about the Arena of Nîmes (history, books, videos and pictures) was obtained by browsing the www and selecting critically what is compacted above starting from references and links reported in [9,10,11].

2.3. Arena of Arles (Arles, France) [12,13]

This arena is a Roman amphitheatre located at Arles, a city in the southern France. Built about 90 AD, has structural and historical similarities with the not far Arena of Nîmes. After the fall of the Roman Empire also Arles suffered a series of invasion by Visigoths, Barbarians and Saracens from the fifth to the ninth century. During the medieval age defensive walls were built around the amphitheatre and buildings were erected inside (a town within a town). Four watching towers were built at the perimeter of the amphitheatre. Three of them are still in place. Between 1826 and 1830 buildings were removed to clear the place out and to make it an amphitheater in function again. It hosted a first bullfight in 1830 and continues to host them today. Figure 6 shows an external view (left) and an internal view (right) of the Arena of Arles. Festivals (*Ferias*) are organized periodically in the arena. They are focused mostly on bullfighters and bullfighting and also on shows of bulls and horses. Among others, an important event is the Feria du riz (Rice Festival) with the now traditional Goyesque bullfight; three forms of art are joined: bullfighting, painting and music. Goyesque refers to the fact that bullfighters and dames dress clothes inspired by those depicted by the famous Spanish painter Francisco Goya. Arles is a musical town, however today musical events are seldom held in the arena. They are hosted in the remains of the ancient Roman theatre, in streets, in churches and other places. In the past some lyric operas have been staged in the Roman amphitheatre. Episodically pop and rock concerts are offered to public. Figure 7 (left) displays a bullfight with musicians and singers.

They perform usually excerpts of Bizet's Carmen and other pieces of circumstance with a Spanish flavour. The right side of Figure 7 shows the set-up of the arena for a concert of Gipsy Kings, a famous pop-flamenco band that started up in Arles more than 25 years ago [14].

Arles Arena receives continuous structural surveillance and maintenance. Information about the Arena of Arles (history, books, videos and pictures) was obtained by browsing the www and selecting critically what is compacted above starting from references and links reported in [12,13].

2.4. Pula Arena (Pula, Croatia) [15,16,17]

This arena is a Roman amphitheatre located at Pula, a town situated at the southern tip of the Istria peninsula (northern Adriatic Sea). The end of its construction is dated about 81 AD under the Roman emperor Titus. When gladiatorial fights and other cruel activities were prohibited (about 5th century) the arena was almost abandoned and the local populace began to plunder its stones. This activity was stopped effectively during the13th century. After the fall of the Roman Empire Pula has had a troubled history. Several rulers of the town have succeeded, however what is important for the monument is that the General Auguste de Marmont, as French governor of the Illyrian Provinces, started the restoration of the arena. This was continued in 1816 by the Ticinese architect Pietro Nobile, commissioned by the emperor Francis I of Austria.

In 1932, the arena was adapted for theatre productions, military ceremonies and public meetings. Figure 8 shows an external view (left) and an internal view (right) of the Pula Arena as it stands today.

The external view in Figure 8 displays the side of the arena that looks toward the Adriatic Sea. It consists of three stories. The opposite part has only two stories because the amphitheatre was built on a slope.

In recent times the arena has been the venue where important opera singers have performed with orchestral accompaniment. To name a few: Luciano Pavarotti, Placido Domingo, Josè Carreras. Also pop/rock concerts of international artists, e.g. Elton John, Tom Jones, Sting, David Gilmour, Zucchero, Paco De Lucia, Joe Cocker and many others, have played in Pula Arena.

Every summer Pula Arena becomes a preferred site for public projection of movies. A festival known as Pula Film Festival is organized since 1954 therein. Croatian film industry awards are also presented traditionally at this festival. Festival concept and award categories were modeled after the U.S.A. Academy of Motion Picture Arts and Sciences (Oscars).

Figure 7. *Arena of Arles. A bullfight with musicians and singers (left). A concert of Gipsy Kings (right).*

Figure 8. *Pula Arena. An external view (left) and an internal view (right).*

Also two professional ice hockey games were played in Pula Arena on September 14 and 16, 2012

These sport events required the installation of a complicated outdoor ice rink.

Figure 9 shows two different main uses of Pula Arena. The left side is related to an opera singer with orchestra (Luciano Pavarotti) and the right side refers to film projections during a Pula Film Festival.

Information about the Pula Arena (history, books, videos and pictures) was obtained by browsing the www and selecting critically what is compacted above starting from references and links reported in [15,16,17].

2.5. El Djem Arena (El Djem, Tunisia) [18,19,20]

This arena is a Roman amphitheatre located at El Djem (Tunisia), a town of Punic or, perhaps, Berber origin known as Thysdrus in Roman times. The date of construction of the amphitheatre is uncertain and doubts are cast if it was completed after the death of Gordianus I who promoted its construction probably between 230 and 238 DC. Nevertheless, it was used in its state mainly for gladiatorial fights and chariot races. The monument remained fairly intact until the 17th century when many stones were taken away for buildings in the nearby village of El Djem and used also for the Great Mosque in Kairouan. A damage of the amphitheatre had been caused in 1695 by cannon fire when troops under the Ottomans flushed rebels out of the amphitheatre then used as a fortress. Actually, a continuous maintenance preserves the integrity of the monument. Figure 10 shows an external view (left) and an internal view (right) of the El Djem Arena as it stands today.

Beside tourist visits to the Roman amphitheatre at El Djem, only The Festival international de musique symphonique d'El Jem is offered as a public show. The symphonic music festival is held every summer since 1985. Many national and international orchestras have participated in the festival, e.g. the Algerian National Symphony Orchestra, the Rome Philharmonic Orchestra, the Tunisian Symphony Orchestra, the Budapest Gypsy Symphony Orchestra and the Orchestra Sinfonica di Roma. Figure 11 shows two photos shot during symphonic concerts in the amphitheatre.

Figure 9. *Pula Arena. Opera singer Luciano Pavarotti (left). Film projection during a session of the Pula Film Festival (right).*

Figure 10. *El Djem Arena. An external view (left) and an internal view (right).*

Figure 11. El Djem Arena. Set-ups of the arena for symphonic concerts.

El Djem Arena receives continuous structural surveillance and maintenance. Information about the El Djem Arena (history, books, videos and pictures) was obtained by browsing the www and selecting critically what is compacted above starting from references and links reported in [18,19,20].

3. ABOUT THE ACOUSTICS OF AMPHITHEATRES IN MODERN USE

The brief highlights on modern use of the five amphitheatres reported in the previous section reveal the wide variety of modern shows offered to public. It is hard to say if natural acoustics play an important role in the desirable fruition of each type of performance. Obviously, in ancient times clangours of blades and shields, shouts of fighting gladiators, roars and growls of tigers and lions, emissions of other exotic animals and cries of cruel executions of criminals were the sound coming from the arena. In some instances also the noise of races of Roman war-chariots was a further sound coming from the arena. However, often the roaring of thousands and thousands of spectators pervaded the crowded amphitheatre. Of course the sound quality in the site, as meant for Roman theatres, was not an interesting matter indeed for builders, although musical intermissions played in the arena may have entertained spectators during ceremonies, changes of games and dining pauses of gladiators. In general, the natural acoustic of an amphitheatre is defective of useful reflected sound energy. Borrowing scientific results from the research on open-air ancient theatres, an amphitheatre in a good state of conservation compared to a Roman theatre, also in a good state of conservation, lacks important structural components which contribute useful reflected sound energy [21]. The high stage building (*frons scaenae*), the stage canopy, the *orchestra* and the vaulted colonnade behind the highest rows of the cavea are absent in amphitheatres. Furthermore, for Roman amphitheatres in modern use, except shows implying the use of the whole arena, performers occupy a stage placed toward a narrow end of the oval/elliptical arena. A non directional sound source located at the centre of the stage platform of a Roman theatre produces almost the same level of the direct sound at each tier order of seats of the cavea. The analogous location of the sound source on the stage of a Roman amphitheatre produces a more irregular distribution of the direct sound because of the elliptical/oval distribution of the seats. What makes a major difference are the larger dimensions of an amphitheatre with respect to a Roman theatre in use for public shows. Table 1 reports the main dimensions and capacity of the amphitheatres considered previously as given by Golvin [22].

For the Overall dimensions, the first number refers to the length of the major axis of the whole oval/elliptical cavea (longitudinal extent) and the second number

Table 1. Dimensions and seating capacity of the considered amphitheatres [23].

Amphitheatre	Overall (m)	Arena (m)	Seating capacity
Verona Arena	152.4 x 123.2	75.7 x 44.4	20226
Arena of Nîmes	133.4 x 101.4	69.1 x 38.4	21349
Arena of Arles	136.2 x 107.6	69.1 x 39.65	23354
Pula Arena	123 x 96.5	67.9 x 41.7	17746
El Djem Arena	147.9 x 122.2	64.5 x 38.8	30573

corresponds to its minor axis (transversal extent). The meaning is the same for the pair of numbers of the sole Arena. The Seating capacity coincides with the maximum number of seated spectators. Typical Roman theatres where public shows are organized, classical music and opera included, are e.g. the Roman theatre at Aspendos (Belkis, Turkey) and the Roman theatre at Orange (Dept. Vaucluse, France). These two theatres are in a very good state of conservation and can be classified among the large ones. Both are praised for their acoustics. Figure 12 shows the plans of the Roman theatres at Aspendos and Orange.

The diameter of the cavea of Aspendos is 95.48 m with a seating capacity of 7650 while for the Orange it is 103.63 m with a seating capacity of 7300 [24]. The dimensions and capacity concerning the pair of Roman theatres, compared with the data in Table 1, suggest some difficulty of feeding all the audience in an amphitheatre with adequate natural sound. Unfortunately, the objective acoustics, evaluated with acoustic measurements and computer simulations, are reported in the available literature only for the theatre at Aspendos. The results in terms of acoustic parameters defined in the document ISO 3382 [25] seem to confirm enough the suitability of the venue for the shows held therein [26]. When the whole arena of an amphitheatre is not used for shows like parades and bullfights, a stage platform is mounted and spectators are arranged mostly on bleachers of the cavea and in part on the ground of the arena. The demand of suitable acoustics is critical for opera and orchestral music. However, there are some doubts that the natural acoustics can fulfil the needed requirements. A first inadequacy may be the loudness perceived at each listener location. Listeners nearer to the stage are favoured. Alike in large Roman theatres, the decay of the sound level vs. the distance from the sound source on the stage may follow nearly the free field law at mid frequencies with a shift toward a lower attenuation of about 2-3 dB. A good signal to noise ratio (S/N) associated with the local attenuation is of paramount importance. Actually, this depends on specific circumstances. An instrumental *pianissimo*, like the one of the 1st violin in the opening bars of the prelude of *Aida*, may be masked by local noise and even by the breathing noise of the audience [27]. A *tutti fortissimo* passage may be heard everywhere in the venue, however the probable lack of the sensation of reverberance determines a poor experience for the listeners. The sound is perceived too dry both by the audience and by the musicians, The latter may have difficulties of intonation and ensemble. Conversely, when the performance is audible, the clarity, although excessive, would not be the main problem in amphitheatres. Concerts of pop, rock and jazz music are amplified with electroacoustic systems in almost all the five amphitheatres considered in this paper. The performers are used to play in open air stadiums, squares, streets, so they need the equipments to which they are accustomed including also the desired non acoustic effects (e.g. light and smoke plays and giant screen projections). What can appear a little surprising is the fact that in the same amphitheatres opera singers and classic orchestras are supported by artificial amplification to overcome the intrinsic deficiency of loudness. This happens also in some ancient open air theatres like e.g. Epidaurus, Taormina and Segesta [28]. Recently, Verona Arena has been endowed with a special electroacoustic system that - unnoticed explicitly - provides also ambience to the benefit of audience and performers during opera seasons [29]. So the locutions “*marvellous acoustics, perfect acoustics*” attributed often by laypersons to some ancient theatres and amphitheatres becomes a mere chimera. Probably, these opinions stem from hearsay influenced also by the old myth that ancient builders were holders of a special scientific wisdom [30]. However, experts and music critics pinpoint acoustic deficiencies especially for opera performance. Only one paper concerning with the quantitative acoustics of amphitheatres dedicated to modern shows, specifically the Verona Arena considered here, was found in the open literature [31]. The authors report extensive results of acoustic measurements,

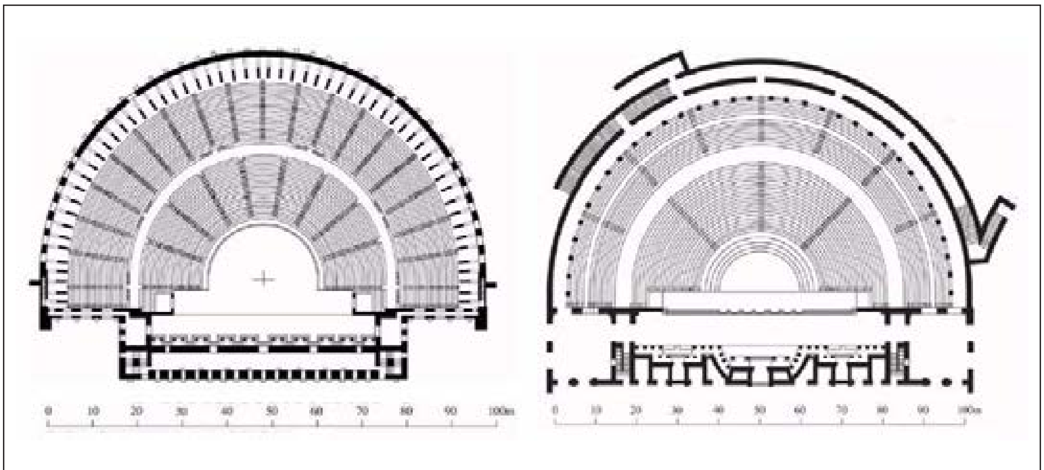

Figure 12. *Plans of the two considered Roman Theatres. Aspendos (left); Orange (right). Modified from [24] and [25] respectively.*

both in the unoccupied amphitheatre and occupied condition with a lesser number of receiver locations. The main aim of the research was the analysis and the suggestion of remedial measures to improve the listening of the balance of the various instrumental sections in the orchestra pit (violins, brasses, percussions...). To the knowledge of the author, among a number of suggestions, the one that was really implemented substantially consisted in the shortening of the transversal length of the orchestra pit and the enlargement of the longitudinal dimension keeping constant its total area. This operation reduced the complains that aroused since decades before. The paper [31] describes focusing and anomalies of sound distribution in the huge amphitheatre in the unoccupied condition. Echoes were heard at various listener areas. However, it is reported that these acoustic drawbacks might be mitigated somewhat by the full occupation of the amphitheatre. Furthermore, negative opinions about the use of Verona Arena for opera performance expressed by third parties are cited. Although not used today for public shows continuously, except a concert of Paul Mc Cartney for 400 selected spectators in 2003 and sporadic ceremonies, it is worth to report that a study and acoustic measurements were carried out also for the Coliseum in Rome, the largest amphitheatre famous worldwide [32]. The authors used an acoustic camera (a beamforming spherical array with 120 microphones) to obtain values of the reverberation time, mostly in the octave bands at 500 and 1000 Hz, and other acoustical features of the amphitheatre as well. Computer simulations and even classical formulas for the calculation of the reverberation time were used to present data. However, the content of the paper [32] needs much more clarification to understand the acoustic behaviour of the Coliseum in more depth. A recent paper [33], except the use of classical formulas for the calculation of the reverberation time, is substantially similar to the previous one.

4. CONCLUSION

Although a number of Roman amphitheatres are used today for the representation of modern public shows implying their acoustics, the content of the present paper confirms that very little attention has been given to their acoustics in the published literature. Otherwise Greek and Roman theatres have been studied with an increasing interest since decades ago; in many instances also with the support of public funding. The five amphitheatres were selected because they host public modern shows regularly during summertime. After a brief description of the monuments and the typical offer of shows of each one, qualitative considerations about their possible acoustics have been dealt with. For the sake of the analysis, reference was made to two large Roman theatres which are in a good state of conservation. These venues offer seasonal cycles of shows and are accredited for their good acoustics. The structural difference between a Roman unroofed theatre and a Roman amphitheatre, both in a good state of conservation, is responsible of a lack of useful reflected sound which is worse in the amphitheatre. The different dimensions, at least for the cases considered in this paper, determine an insufficient sense of reverberation and perceived loudness. Musical events like opera and classical music would need specific acoustic conditions that are far to be fulfilled by the natural acoustics of the considered amphitheatres. The insufficient loudness is compensated with the support of suitable electroacoustic systems. It was a little surprise to ascertain that, besides the considered amphitheatres, also well known unroofed Greek and Roman theatres are endowed with artificial amplification, e.g. for drama, comedies, and music performed with unamplified instruments. The perfect natural acoustics alleged by many laypersons remains a die hard myth. However, one must conclude that the acoustics for golden ears can lose its importance when spectators live a unique global experience in amphitheatres. An opera, a symphony under a quiet starry night, the being there conscious of togetherness, the beauty of the scenery evoke emotional involvements that downgrade the rank of the pure listening.

REFERENCES

[1] URL: https://www.coe.int/t/dg4/cultureheritage/heritage/resources/Texts/Verone_EN.pdf, accessed 2016-08-06.

[2] ERATO project. Evaluation and Revival of the Acoustical heritage of Ancient Theatres and Odea. (Contract Number ICA3-CT-2002-10031), financed by the European Commission under the Fifth Framework INCO-MED Program.

[3] ATHENA project of Ancient THeaters Enhancement for New Actualities supported and funded under the Euro-Med Heritage IV program by the European Commission and supervised by its Regional Monitoring and Support Unit (RMSU).

[4] ATLAS project. Ancient Theatres Lighting and Acoustics Support. PRIN 2005 prot. 2005081870 co-funded by MIUR (Italian Ministry of University and Research).

[5] URL: http://www.chicagonow.com/neighborland/2016/07/arles-in-southern-france-fetes-and-romans-and-photographie/, accessed 2016-08-17.

[6] URL: http://www.arena.it/arena/it, accessed 2016-08-17.

[7] URL: https://en.wikipedia.org/wiki/Verona_Arena, accessed 2016-08-18.

[8] URL: https://it.wikipedia.org/wiki/Arena_di_Verona, accessed 2016-08-16.

[9] URL: http://arenes-nimes.com/en/home, accessed 2016-08-16.

[10] URL: https://en.wikipedia.org/wiki/Arena_of_N%C3%AEmes, accessed 2016-08-20.

[11] URL: https://fr.wikipedia.org/wiki/Ar%C3%A8nes_de_N%C3%AEmes, accessed 2016-08-20.

[12] URL: http://www.arenes-arles.com/, accessed 2016-08-25.

[13] URL: https://fr.wikipedia.org/wiki/Ar%C3%A8nes_d%27Arles, accessed 2016-08-25.

[14] URL: http://www.gipsykings.com/#gipsykings, accessed 2016-08-28.

[15] URL:https://en.wikipedia.org/wiki/Pula_Arena, accessed 2016-08-28.

[16] URL: https://fr.wikipedia.org/wiki/Amphith%C3%A9%C3%A2tre_de_Pula, accessed 2016-08-29.

[17] URL: https://en.wikipedia.org/wiki/Pula_Film_Festival, accessed 2016-08-31.

[18] URL: https://en.wikipedia.org/wiki/El_Djem, accessed 2016-09-01.

[19] URL: http://www.famous-historic-buildings.org.uk/tunisia_16.html, accessed 2016-09-02.

[20] URL: https://fr.wikipedia.org/wiki/Festival_international_de_musique_symphonique_d%27El_Jem, accessed 2016-09-05.

[21] M. Lisa, J.H. Rindel, A.C. Gade, C.L. Christensen - Acoustical Computer Simulations of the Ancient Roman Theatres – Proc. Erato Project Symposium Audio Visual Conservation of the Architectural Spaces in Virtual Environment, 20 January 2006, Yildiz Technical University Istanbul, Turkey, pp. 20-26.

[22] Jean-Claude Golvin - L'amphithéâtre romain : essai sur la théorisation de sa forme et de ses fonctions - Paris : Diffusion de Boccard, 1988, pp. 284-288.

[23] URL: https://www.whitman.edu/theatre/theatretour/aspendos/images/large%20images/aspendos.plan.jpg, accessed 2017-01-03.

[24] Frank Sear, *Roman Theatres: An Architectural Study*. Oxford: Oxford University Press, 2006.

[25] ISO 3382-1:2009(E) - Acoustics — Measurement of room acoustic parameters — Part 1: Performance spaces.

[26] A.C. Gade, M. Lisa, C.L. Christensen, J.H. Rindel - Roman Theatre Acoustics: Comparison of acoustic measurement and simulation results from the Aspendos Theatre, Turkey - Proceedings of the18th International Congress on Acoustics ICA 2004, 4-9 April 2004, Kyoto, Japan.

[27] M. Kleiner (1980) - On the audience induced background noise level in auditoria - Acustica, vol. 46, pp. 82-88.

[28] Carlo Trabia - Greek Amphitheatre Acoustics – Best of Sicily Magazine (2007). URL: http://www.bestofsicily.com/mag/art233.htm visited October 24, 2016.

[29] CONNESSIONI Magazine- OS-1 FOR THE ARENA DI VERONA: The system which is present but can't be heard - August/September 2013/Year 8th/n.16, pp. 32-40. URL: https://issuu.com/connessionidigital/docs/connessioni_16_20130809 visited November 4, 2016.

[30] Carmine Ianniello - L'acustica degli auditori: arte, scienza o mito? I tempi dei teatri greci e romani - Atti del 1° Convegno Nazionale Storia dell'Ingegneria, tomo II pp. 811-820, Napoli 8-9 Marzo, 2006.

[31] Cognini M., Farina A., Pompoli R. – L'ACUSTICA DELL'ANFITEATRO ROMANO "ARENA DI VERONA" – Atti della Conferenza Internazionale Acoustics and recovery of spaces for music, CIARM93, Ferrara 27-28 Ottobre 1993.

[32] Mojtaba Navvab, FabioBisegna, Gunnar Hilmann and Magdalena Böck - DYNAMIC VARIATIONS OF DIRECT AND REFLECTED SOUND PRESSURE LEVELS USING BEAMFORMING - BeBeC-2012 -28, in Proceedings of the 4th Berlin Beamforming Conference, Berlin, February 22-23, 2012.

[33] Mojtaba Navvab, Fabio Bisegna and Franco Gugliermetti - CAPTURING ANCIENT THEATERS SOUND SIGNATURE USING BEAMFORMING - in Proceedings of ICSV23, The 23rd International Congress on Sound and Vibration, Athens, Greece, 10-14 July 2016.

Relevance of acoustic Performance in Green Building Labels and social Sustainability Ratings

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ABSTRACT

Several initiatives have been launched to increase sustainability in the building industry. All of them contain a shift in focus from energy consumption during use phase to a wide variety of indicators for the full life cycle of a building. This implies a broader view of sustainability, not only based on the ecological, but on the economic and social performance of buildings as well.

A closer look on internationally acting Green Building Labels reveals that acoustic performance is, although a technical quality, seen as part of the social sustainability aspects of a building. Depending on the label, several credits are assigned for the fulfilment of requirements with different levels of severity.

It can be shown that noise protection within and from outside the building is seen as an important aspect of social sustainability. Thus, the approach of how to consider acoustic performance of buildings and impact on rating results of Green Building Labels vary heavily.

1. INTRODUCTION

The objective of Nearly Zero Energy Buildings (NZEB) of the EU Energy Performance of Buildings Directive will become legally binding in 2020 for all new buildings. This can be seen as a significant leap for the construction sector [1]. The importance of a more pronounced focus on sustainability in the building industry is proved by the fact that it contributes to more than 40 % of pan-European mass and energy flows [2]. In general, buildings and structures need 50 % of all natural resources utilized, as a consequence of their production, building, usage and maintenance. They create around 60 % of all wastes and are responsible for 40 % of worldwide greenhouse gas emissions [3]. These figures show the importance of the building sector's environmental impacts.

Nowadays holistic approaches include, beside energy use and Greenhouse gas emissions, aspects of economic and social sustainability. According to the general definition of sustainability ecological, economic and social aspects and consequences – also called the "three columns of sustainability" – are taken into account to analyse and assess buildings (figure 1). This is already pictured in relevant voluntary, horizontal standards for the assessment, developed by CEN/TC 350 "Sustainability of construction works" since 2005 according the European Commission's mandate [4] with all aspects of sustainability included.

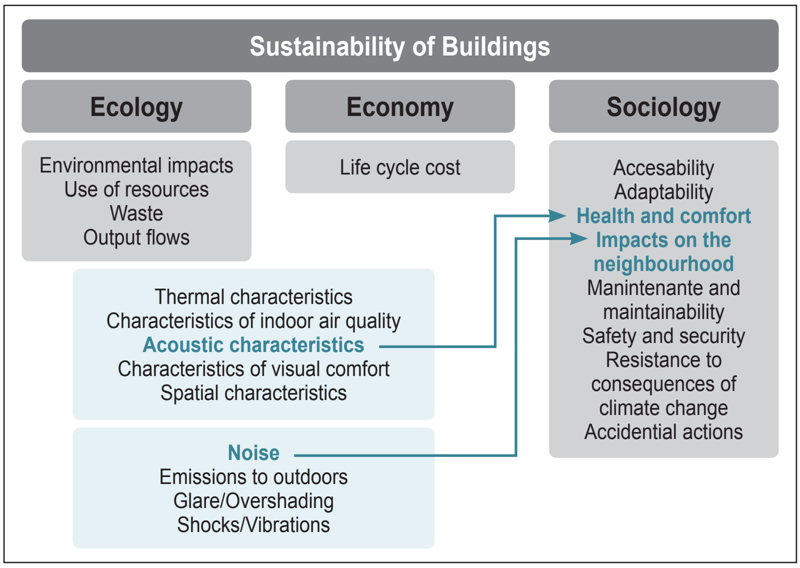


Figure 1. *Three columns of sustainability with respective aspects for analysis (Own drawing, based on sustainability aspects according to EN 16309).*

A different strategy with the same goal of achieving transformation to a more sustainable building sector can be seen in Green Building Labels (GBLs), assessment and rating schemes which can be characterized according to Sinha et al. [5] as integrated building practices that aim to significantly reduce the environmental footprint of a building in comparison to standard practices.

2. METHODOLOGY

Sustainability assessment of buildings is related to a variety of different issues. One of them is the acoustic performance of the analysed structure, the surroundings and service equipment. The aim of this paper is to analyse how acoustic performance is assessed in different GBLs and relevant standards. The focus of investigation was on labels from German speaking countries and labels with significance beyond the borders of their country of origin. The objective was to figure out, if sound protection is seen as an important issue of sustainability, which acoustic characteristics are considered and which methodological approaches are used for rating. Analysis is based on the GBLs web pages and publications on criteria, assessment and credits. To find out the impact of acoustic properties on GBL's rating results, the different assessment schemes had to be investigated. Finally, interrelation between acoustic performance of building components and the environmental impact of building materials, calculated according to life cycle assessment (LCA) methods, was studied. LCA is based on calculations using Ecosoft v5.0 software [6] with baubook database [7] and own data from ECO2/ecotimber research project [8]. They cover production phase from cradle to gate (A1 to A3) according EN 15978 [9].

3. STANDARDISATION OF ACOUSTIC PERFORMANCE AS SUSTAINABILITY CRITERIA

Though noise is a subjective phenomena and strongly related to the individual perception, surveys, carried out in different European countries and summarised by Lang in [10] show annoying acoustic situations for a significant amount of inhabitants. Figures from the European Commission indicate that more than 100 Million people are exposed to annoying sound levels with different resulting effects like hearing impairment, hypertension, heart disease, annoyance, and sleep disturbance [11]. Considering the importance of this topic for health and wellbeing, noise protection became an important indicator for social sustainability aspects of buildings.

The respective standard, EN 16309 "Sustainability of construction works –Assessment of social performance of buildings– Calculation methodology" [12], does not give benchmarks. Instead it provides information about what and how to assess by suggesting related standards for calculation, measuring and single number rating for the assessment of acoustic characteristics. A closer look at this standard shows that so called "Acoustic characteristics" are a subchapter in "Health and Comfort" in the "Methods for assessment of social performance" section (figure 1). There, they are one out of several social aspects like indoor air quality and thermal characteristics that are related to building physics. However, the section also contains qualitatively assessed aspects like visual comfort and spatial characteristics.

3.1. EN 16309:2014 Chapter 7.4.4 Acoustic characteristics

According to EN 16309, acoustic characteristics are defined by airborne and impact sound insulation of separating walls and floors, sound insulation of the external envelope, noise level including service equipment noise, and reverberation time. Further it is mentioned that different types of use shall be taken into account. A detailed overview of recommended aspects and standards for evaluation is given in table 1.

An additional note states that acoustic quality of a building can be determined by calculation using EN 12354 series of standards or through measurements in laboratories or in situ. It is indicated that the acoustic performance of the building varies heavily with the quality of workmanship and the actual situation encountered and that laboratory measurements depend on testing accuracy.

3.2. EN 16309:2014 Chapter 7.5.2 Noise

Further acoustic related aspects can be found in the chapter "Impacts on the neighbourhood" in the subchapter called "Noise" (figure 1). It is aimed at noise emissions from the building and a resulting disturbance of the neighbourhood. As the relevant descriptor the emitted sound pressure level in dB(A) is suggested. In case the assessment is based on a design, sound insulation and sound barriers should be examined for their potential to contribute to control of noise emitted from the building.

4. GREEN BUILDING LABELS

Green Building Labels (GBLs) are voluntary, third party certification schemes which assess sustainability of buildings with numerous indicators for ecologic, economic and social performance. They have the aim to assess how well a building or a building project meets a specified set of sustainability aspects by developing a certification system. Each of these aspects is addressed by various indicators and benchmarks. These certification schemes can be seen as instruments to assess sustainability with a significant intrinsic marketing potential. Mainly high-class buildings and lighthouse projects are certified for promotional purposes since certification is a complex process causing additional costs. Each system takes the trinity of sustainability into account, but not all of them are already in compliance with the European standards developed by CEN TC 350. The reason for this is that GBLs already existed before related standards were finished or even before European Commission gave mandate to CEN/TC 350 [4] in 2004 to elaborate these kinds of standards. However, the process to adopt these standards by at least the European labels seems to be on the way. Labels chosen for analysis are shown in table 2.

Table 1. *Recommended acoustical aspects and normative assessment methods in EN 16309.*

Acoustical aspects	Calculation	Measurement	Assessment
Sound insulation between rooms: • Airborne sound • Impact sound	 EN 12354-1 EN 12354-2	 EN ISO 10140-2, EN ISO 16283-1 EN ISO 10140-3 EN ISO 16283-1*	 EN ISO 717-1 EN ISO 717-2
Sound insulation against airborne sound from outside to inside	EN 12354-3	EN ISO 16283-1*	EN ISO 717-1
Sound levels from service equipment and other sources of ambient noise	EN 12354-5		
Room acoustics: • Sound absorption in enclosed spaces • Reverberation time • Room acoustic parameters of open plan offices	 EN 12354-6 EN 12354-6	 EN ISO 3382-2 EN ISO 3382-3	

* EN ISO 16283-1 gives guidance for measurement of airborne sound in situ only. EN 16309 refers to EN ISO 16283-1 for facades and impact sound as well, though these aspects are covered by part 2 and 3, which are still draft versions.

Table 2. *Selection of European and international Green Building Labels analysed (Sources: Ebert et al, 2010 [3], BREEAM [13], DGNB [14], HQE [15], LEED [16], Minergie ECO [17], TQB [18]).*

	BREEAM	DGNB	HQE	LEED	Minergie ECO	TQB
Full title	Building Research Establishment's Environmental Assessment Method	Deutsches Gütesiegel Nachhaltiges Bauen	Haute Qualité Environne-mentale	Leadership in Energy & Environmental Design	–	Total Quality Building
Country of origin	UK	Germany	France	USA	Switzerland	Austria
Established in	1990	2007	1996	1998	2006	2009
Responsible organisation / company	Building Research Establishment (BRE) – former state-run but since 1972 private consultancy	Deutsche Gesellschaft für Nachhaltiges Bauen - association	Association HQE – association	U. S. Green Building Council – non-profit organisation	MINERGIE – public association	Österreichische Gesellschaft für Nachhaltiges Bauen - association
Number of buildings certified	7330 since 2008 (January 2015)	691 (January 2015)	Not available	35.202 (January 2015)	1113 (January 2015)	99 (March 2014)
Number of countries covered	> 50 (65 % in the UK)	20 (85 % in Germany)	Gobal – number not available	135 (80 % in USA)	2: Switzerland (99 %), Principality of Liechtenstein	1: Austria
Current version	2014	2012 (with upgrade 2013)	RB: April 2014 NRB: Sept. 2013	v4 (November 2013)	v1.2 - 2014	TQB.2010

4.1. General characteristics of Green Building Labels

The international network of World Green Building Councils (WGBC) indicates at the time of investigation 100 members from Argentina to Zimbabwe [19], mainly national councils. Green building rating systems are constantly evolving and differ from country to country, but fundamental principles persist from which the diverse methods are derived: location, structure design efficiency, energy efficiency, water efficiency, materials efficiency, indoor environmental quality, operations and maintenance optimization, reduction of waste and toxic substances and cost efficiency. The aim of each label is the optimization of as many of these principles as possible.

In the last few years a shift away from qualitative approaches, towards a scientifically informed, quantitative evaluation of performance through LCA can be determined. Though LCA, a technique to assess environmental impacts associated with all the product's or building's life cycle stages, is widely recognized as the best way to evaluate environmental impacts, it is not yet part of all green building certification schemes. Nevertheless, at least European schemes already use LCA as an assessment method for environmental impacts and provide their users with the required databases, although exhaustive lists of building materials and constructions are still under development.

Apart from databases, calculation tools are made available as well. On the one hand they should facilitate assessment, but on the other hand they should also make sure that data and methods are consistent in order to get comparable results from diverse assessors and buildings. Since different building types require different methods and aspects to consider, each GBL offers systems for several building categories. All given GBLs distinguish indicators and benchmarks for residential and non residential buildings.

Although the general approaches seem to be brought into line, still, rating method and criteria as well as weighting of the different aspects vary heavily within the GBLs [20]. This also applies for acoustic aspects of a building and their significance within the respective certification scheme.

4.2. Impact of acoustic performance on Green Building assessment results

A critical review of some of the most important GBLs with focus on acoustic indicators leads to the conclusion that they influence results of GBLs quite differently (figure 2). Usually indicators follow already standardised descriptors as pointed out in table 3.

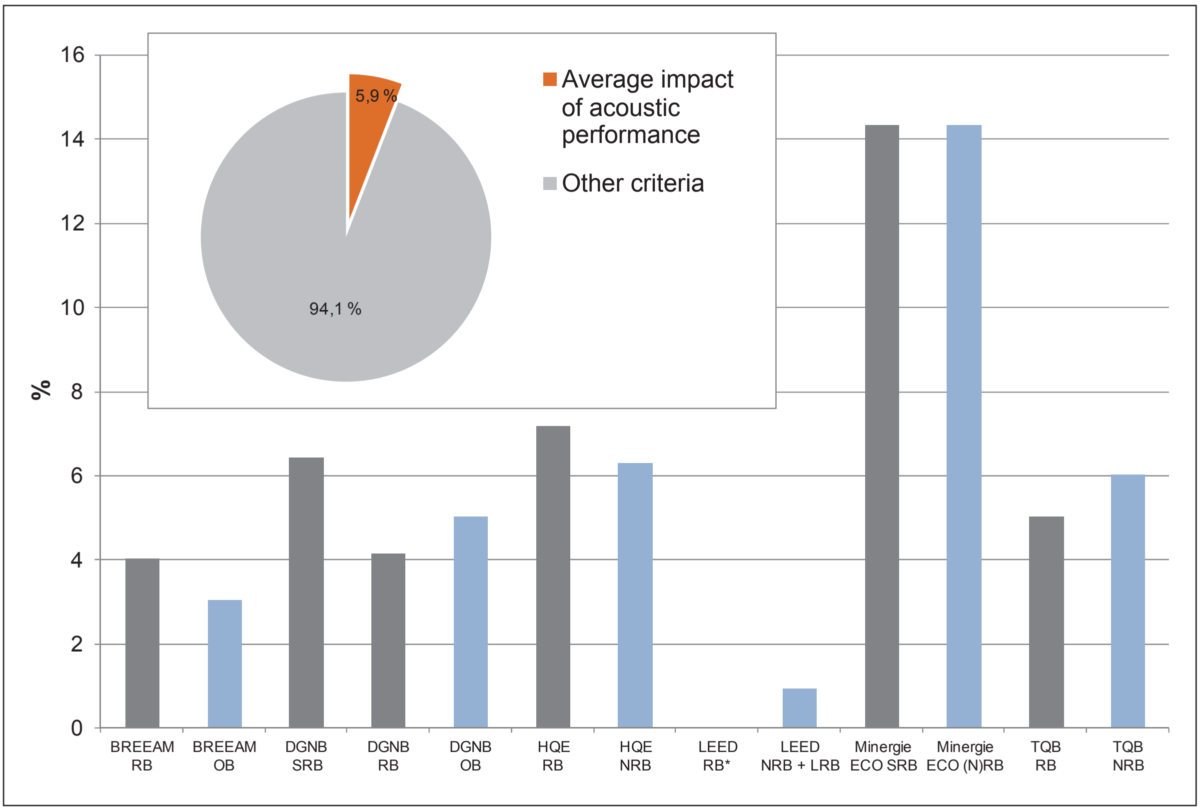


Figure 2. *Average and maximum possible impact of acoustic aspects on results of GBLs for new buildings: Rating schemes for residential buildings (RB, SRB = small residential buildings, LRB = large residential buildings) and non-residential buildings (NRB, OB = office buildings), * = not a mandatory criteria yet (Sources: BREEAM [21], DGNB [22, 23, 24], [25], HQE [27, 28], LEED [29], Minergie ECO [30, 31] ÖGNB (TQB) [32, 33]).*

Table 3. *Indicators, used for assessing acoustic building performance in GBLs for new buildings (Sources: see figure 2).*

Type of indicators	BREEAM*	DGNB	HQE	LEED*	Minergie ECO	TQB
If not mentioned otherwise in brackets rating schemes for…	RB + NRB	RB + NRB	RB + NRB	LRB + NRB	RB + NRB	RB + NRB
Airborn sound insulation of walls	$D_{nT,w}$ + Ctr	R'_{w}	$D_{nT,w}$ + C	STC_{C}	$D_{nT,w}$ + C	$D_{nT,w}$
Airborn sound insulation of ceilings/floors	$D_{nT,w}$ + Ctr	R'_{w}	$D_{nT,w}$ + C	STC_{C}	$D_{nT,w}$ + C	$D_{nT,w}$
Impact sound insulation	$L'_{nT,w}$	$L'_{n,w}$	$L'_{nT,w}$		$L'_{nT,w} + C_{I}$	$L'_{n,Tw}$ (+ $C_{I,50\text{-}2500}$)
Ambient noise – site-related noise level						L_{Aeq}
Sound insulation against airborne sounds from outside to inside		$R'_{w,res}$	$D_{nT,w} + C_{tr}$		$D_{nT,w} + C_{tr}$	$R'_{res,w}$ (RB) $L_{A,95}$ (RB)
Sound level from service equipment	L_{Aeq}	$L_{AFmax,n}$	L_{nAT}	NC	d	$L_{A,eq,nT}$ $L_{C,eq,nT}$ (RB) $L_{AFmax,nT}$ (NRB)
Sound absorption and reverberation time	T (NRB)	T (NRB)	T_{r} (NRB)	T	T (LRB, NRB)	T α_{m} (NRB)
Benefitial layout of rooms						d (RB)
Sound reinforcement and masking systems				STI or CIS		
Absorption area of coverings			EAA			
Protection of outdoor areas					d	

* Or indicators of national standards, if they are more stringent.
RB = residential buildings, NRB = non-residential buildings, LRB = large residential buildings
d = descriptive, qualitative indicator

Not only indicators differ between GBLs; sound protection levels, displayed by benchmarks, are difficult to compare as well. This is shown in table 4 and 5 which indicate examples of benchmarks for separating walls and floors, limited to residential buildings. It is obvious that benchmarks correspond to general noise protection levels in the particular country of origin of the GBL. Generally, focus of the schemes on regional or the international market is reflected by reference documents and resulting benchmarks. Some internationally oriented systems allow application of regional requirements and in case there are none, use of the ones of the GBL's country of origin is permitted. Usually, the calculated acoustic performance has to be proved by pre-completion measurements on site.

BREEAMS's [21] worldwide use as certification system requires a flexible use of benchmarks and standards. For airborne and impact sound insulation in residential buildings the BREEAM system allows use of local building codes. The number of credits that can be obtained depends on exceeding benchmarks positively from 3 (lowest credit) to 8 dB (highest credit). Non-residential buildings are classified according British standard considering indoor ambient noise level, sound absorption and reverberation time.

DGNB's [22, 23, 24, 25] new residential building scheme is sub-divided into small and ordinary houses. Both analyse airborne and impact sound insulation and noise from service equipment. The impact of acoustic performance on overall rating results is higher for the small houses scheme. Assessment of acoustic performance is based on DIN 4109 in addition with the DEGA Schallschutzausweis [26]. The class rating of Schallschutzausweis is transferred to so called checklistpoints (CLPs) which are converted to credits in the DGNB rating system. For non-residential buildings the different acoustic performance aspects are classified in 3 different categories and rated with CLPs which are converted to credits in a similar way.

The French HQE [27] [28] features a relatively complex rating scheme with criteria that are adapted to the international target group. Basic compliance can be achieved by including acoustics in architectural provisions and meeting national regulatory levels. If no such regulations exist, applicants have to stick to local practices and improve them for at least two topics such as airborne or impact sound insulation. Better rating results require adherence with quantitative values for several acoustic indicators. Maximum ratings are bound to improvement of at least 3 to 6 (depending on the building type) of these indicators. Additionally to sound and impact noise as well as sound pressure from equipment the equivalent absorption area of rooms may be assessed.

In the LEED [29] certification scheme, acoustic properties of buildings only play a minor role (figure 1) compared to all the other aspects considered. For two of the several schemes (LEED Homes and LEED Multifamily Midrise), which are designed for smaller residential buildings up to 8 storeys, acoustic indicators are still in a pilot phase and under discussion within assessors. In the LEED New Constructions and Major Renovation scheme, analysed parameters are airborne sound insulation of floors and walls within the building and HVAC background noise. Descriptors are composite sound transmission class (STCC) with given benchmarks to be fulfilled, and A-weighted sound level of service equipment. In non residential buildings, reverberation time is a topic as well. When local building codes are more stringent, they have to be applied in case of given benchmarks from the scheme.

The Swiss Minergie ECO [30, 31] is an extension of the mostly energy-efficiency-based rating tool Minergie. Differently to other GBLs the result of the rating is not expressed by a certain number of points and distinguished into different levels of target deployment (such as bronze, silver, gold and platinum). Instead all criteria have to be fulfilled according to a “traffic light system” distinguishing in “not sufficient” (red), “sufficient” (yellow) and “good” (green). In the end only projects where all criteria are rated either green or yellow are awarded, a red rating results in preclusion. As one of only six equally weighted criteria acoustics play an important role compared to other GBLs. Requirements for airborne and impact sound insulation and noise from service equipment are assessed in two steps according to basic and advanced compliance with the standard SIA 181. Reverberation time is an issue for multi residential buildings and non-residential buildings. A peculiarity of Minergie ECO is the assessment of protection of outdoor areas such as balconies in noise exposed surroundings.

A variety of different acoustic aspects has to be analysed for the Austrian TQB [32] [33] system. Starting with ambient noise of the building’s location during day and night, an acoustically favourable ground plot, airborne and impact sound insulation of floors, internal and external walls as well as noise from service equipment are aspects which have to be investigated. For non-residential buildings, indoor ambient noise has to be analysed additionally. This is carried out by ensuring that the actual reverberation time in the room does not differ more than +/- 5 % from the ideal range in each octave band. Another peculiarity of TQB is that it takes acoustic performance in the lower frequency range below 100 Hz into account, since spectrum adaptation term $C_{I50-2500}$ is considered for impact sound insulation. The reason for that can be seen in some years of experience with a voluntary classification scheme of acoustic building performance (ÖNORM B 8115-5) including frequencies from 50 to 100 Hz in the higher classes. Achieving requirements according to local building code yields no credits at all, but shortfall is a reason for preclusion. Predicted acoustic performance has to be proved by a predefined amount of in situ measurements.

4.3. Comparison of acoustic requirements for building components in Europe: National benchmarks and Green Building Labels

As already mentioned, for many GBLs it is sufficient to fulfil national acoustic requirements according to national building codes or standards. However, some of them take a step ahead in order to improve annoying noise situations for inhabitants in changing vicinity with urban densification, increasing volume of traffic, new, financially optimised building structures and home entertainment equipment. Therefore, requirements of some European GBLs were analysed exemplarily and compared to respective national requirements. Results of the analysis are shown in tables 4 and 5 for different labels.

Whilst German DGNB requirements follow the recommendations of DEGA Schallschutzausweis [26], Minergie ECO system requests achievement of Swiss SIA 181 benchmarks with different sound insulation categories. The Austrian TQB shows requirements which are way more demanding than the respective building codes claim. To achieve the best possible rating, for $L'_{nT,w}$ the 50 to 100 Hz frequency range with $C_{I50-2500}$ has to be taken into account.

5. SOUND INSULATION AND LCA - CASE STUDIES ON ACOUSTIC QUALITY AND ENVIRONMENTAL IMPACT OF BUILDING ELEMENTS

As shown in previous chapters, improved sound insulation is reflected directly in the criteria, but it also has impact on the ecologic quality of a building. The most important method to improve sound insulation of

***Table 4.** Example of acoustic benchmarks – for new residential buildings – separating walls, airborne sound (Sources as in figure 2).*

	Indicator	Benchmark in standard of origin*	Minimum requirement of GBL	Best rating results of GBL
BREEAM	$D_{nT,w} + C_{tr}$	≥ 45 dB	≥ 48 dB	≥ 53 dB
DGNB	R'_{w}	≥ 53/54 dB	≥ 53/54 dB	≥ 62 dB
HQE	$D_{nT,w} + C$	≥ 53 dB	≥ 53 dB (depending on type of room)	–
MINERGIE ECO	$D_{nT,w} + C$	≥ 52/55 dB (rented/owned)	≥ 52/55 dB (rented/owned)	≥ 52/55 dB (rented/owned)
TQB	$D_{nT,w}$	≥ 55 dB	≥ 55 dB	≥ 64 dB

* Acoustic requirements of GBL's country of origin according to [10] and [34].

***Table 5.** Example of acoustic benchmarks – for new residential buildings – floors, impact sound (Sources as in figure 2).*

	Indicator	Benchmark in standard of origin*	Minimum requirement of GBL	Best rating results of GBL
BREEAM	$L'_{nT,w}$	≤ 62 dB	≤ 59 dB	≤ 54 dB
DGNB	$L'_{n,w}$	≤ 53 dB	≤ 53 dB	≤ 40 dB
HQE	$L'_{nT,w}$	≤ 58 dB	≤ 58 dB	-
MINERGIE ECO	$L'_{nT,w} + C_{I}$	≤ 53/50 dB (rented/owned)	≤ 53/50 dB (rented/owned)	≤ 53/50 dB (rented/owned)
TQB	$L'_{nT,w}$ $C_{I,50\text{-}2500}$	≤ 48 dB	≤ 48 dB	≤ 37 dB < + 1 dB

* Acoustic requirements of GBL's country of origin according to [10] and [33].

a component is to add mass or a mass-spring-system. Both measures lead to an increased amount of material with related environmental impacts over the whole life cycle. A case study on typical walls illustrates the relation between environmental impact and acoustic performance.

A solid wood wall is modified with the aim to improve the acoustic performance. Starting with the raw cross laminated timber board (CLT) (1), an improvement of R_w can be reached by mounting a flexible shell with the cavity filled with mineral wool (2). In a further step, the shell is separated completely from the CLT element (3). In another variation, insulation in the cavity is replaced by cellulose fibre, a recycling product (4). In addition, a concrete wall with flexible shell is analysed to show different results for mineral structures (5) (table 6).

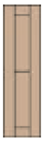
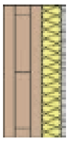
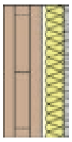
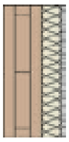
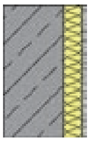
The LCA calculations reveal the interconnection between acoustic performance and environmental impact of the different measures. Figure 3 shows environmental impact (through a selection of relevant indicators) and acoustic performance (sound reduction index R_w).

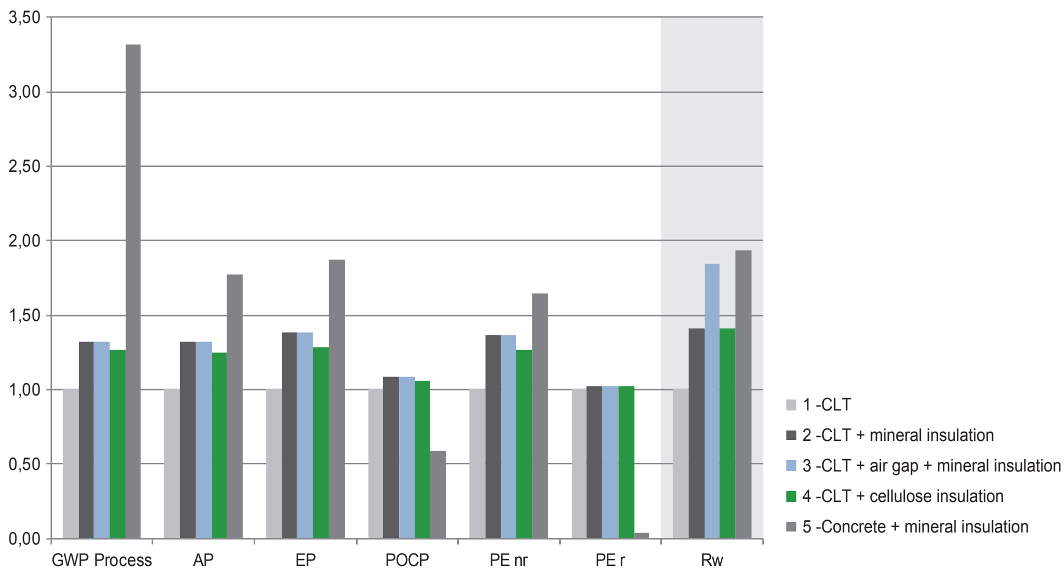
The results of this brief case study show that, at least for this type of constructions, a higher amount of layers in the structure usually improves acoustic performance, but decreases the environmental one. However, simple measures such as an air gap without any ecological impact can lead to higher sound insulations as well. Furthermore, results indicate that use of appropriate and possibly renewable materials with smaller environmental impacts during production process such as cellulose insulation and a longer service life (in case the whole life cycle is considered) may be most beneficial for the environment and may at the same time improve credits for ecological sustainable constructions. Finally it has to be pointed out that measures to improve R_w do not necessarily lead to higher sound insulation beyond the respective normative frequency spectrum.

6. CONCLUSIONS

Sustainability in the construction sector is no longer reduced to low energy demand during use phase of a building. Meanwhile the whole life cycle from raw material extraction to end of life (cradle to grave) and beyond is considered. Moreover the definition of sustainability is extended from ecology to further aspects of economic and social sustainability. All these

Table 6. *Description of analysed walls.*

	Profile of wall constructions	Composition of walls	Sound reduction index R_w
1		100 mm CLT	32 dB
2		100 mm CLT 50 mm steel stands, cavity filled with mineral wool 12,5 mm gypsum plaster board	45 dB
3		100 mm CLT 10 mm air gap 50 mm steel stands, cavity filled with mineral wool 12,5 mm gypsum plaster board	59 dB
4		100 mm CLT 50 mm steel stands, cavity filled with cellulose insulation 12,5 mm gypsum plaster board	45 dB
5		160 mm reinforced concrete 50 mm steel stands, cavity filled with mineral wool 12,5 mm gypsum plaster board	61 dB



GWP Process: global warming potential, expressed in kg CO_2-equivalents, includes all emissions during the production process, carbon stored in organic building materials not considered
AP: acidification potential expressed in kg SO_2-equivalents
EP: eutrophication potential expressed in kg PO_4-equivalents
POCP: photochemical ozone creation potential expressed in kg C_2H_4-equivalents
PE nr: primary energy demand from non-renewable (fossil) sources expressed in MJ
PE r: primary energy demand from renewable sources expressed in MJ
Rw: sound reduction index expressed in dB

Figure 3. *Environmental impact and acoustic performance of walls with different measures to improve sound insulation, calculated for production (before use) phases A1-A3 according to EN 15978 [9] and converted into an index with wall 1 (CLT only) as base value (1,00).*

aspects are already covered by a set of voluntary, horizontal standards where acoustic quality of a building is seen as an important issue, summarised under social building performance.

GBLs are voluntary, usually private, certification schemes for sustainability of buildings which already exist since the 1990s. They do not fulfil mentioned standards mainly because these standards are much younger than the systems themselves. Nevertheless, each of them has its own (and different) approach to building acoustics, usually strongly related to the national regulations of the country of their origin. The respective survey of GBLs shows that most of them demand fulfilment of national requirements. More ambitious certification schemes, usually implemented in countries with advanced building acoustic standards, go beyond established standards.

As proved in this survey, efforts for higher acoustic quality of building components can have impact on the ecological performance of the whole building and counterbalance advantages already gained in the rating. Therefore, measures to improve sound insulation of a component always have to be considered comprehensively. Opportunities for solid wood walls have been shown in the paper, but in general, application of renewable materials with comparable properties can be seen as the easiest method to decrease ecological impact.

Harmonisation of GBLs can't be expected in the medium term since this inevitably would lead to the loss of their unique selling point. However, standards will be adopted by at least the European labels step by step. Acoustic aspects and benchmarks won't be harmonised as long as there are no common standards for building acoustic quality in Europe. This leads to the interesting situation, that an assessed building can be forced to fulfil the acoustic requirements of a label which are more demanding than the national ones. Considering this, GBLs seem to provoke some kind of movement and, in the best case, knowledge transfer about better sound insulation and noise protection in buildings.

7. REFERENCES

[1] Kuittinen M., et.al. (ed.): Wood in carbon efficient construction. Tools, methods and applications. CEI-Bois. Brussels 2013. ISBN: 978-9-0820-9080-2.

[2] Wittstock B., Albrecht S., Colodel C. M., Lindner J. P.: Gebäude aus Lebenszyklusperspektive - Ökobilanzen im Bauwesen. In: Bauphysik 31. Ernst und Sohn (31), S. 9–17. Berlin 2009.

[3] Ebert T., Eßig N., Hauser G.: Zertifizierungssysteme für Gebäude. Nachhaltigkeit bewerten. Internationaler Systemvergleich. Zertifizierung und Ökonomie. Institut für internationale Architektur-Dokumentation GmbH und Co-KG. Redaktion DETAIL. München 2010.

[4] European Commission (DG ENTR) (ed.): Standardization Mandate to CEN - M/350 EN, development of horizontal standardized methods for the assessment of the integrated environmental performance of buildings. Brussels 2004.

[5] Sinha A., Gupta R., Kutnar A.: Sustainable development and green buildings = Održivi razvoj i zelena gradnja. Drv. ind., 64(1): 45-53. 2013.doi: 0.5552/drind.2013.1205

[6] Österreichisches Institut für Baubiologie und -ökologie. "ECOSOFT 3.4.2: Software for the ecological assessment of building components and buildings". http://www.ibo.at/de/ecosoft.htm, actual version: ECOSOFT 5.0, including IBO-database. Vienna 2012.

[7] baubook – The database for ecologic construction and renovation. baubook GmbH. http://www.baubook.info - Tools for environmental product selection. Vienna 2012.

[8] Dolezal F., Mötzl H.: ECO2/ecotimber – Wood in sustainable constructions. Final report. Österreichische Forschungsförderungsgesellschaft FFG. Project 839368. Vienna 2013.

[9] EN 15978: 2012 Sustainability of construction works - Assessment of Environmental performance of buildings – Calculation method. European Committee for Standardisation.

[10] Lang, Judith: Schallschutz in Europa. In: Bauphysik Kalender 2014: Raumakustik und Schallschutz. S. 121-182. Ernst & Sohn GmbH und Co. KG. Berlin 2014. ISBN: 978-3-433-03050-9.

[11] Schulte-Fortkamp. Brigitte: Lärm bzw. Schallwirkung auf den Menschen und die Notwendigkeit des Schallschutzes in Gebäuden. In: Bauphysik Kalender 2014: Raumakustik und Schallschutz. S. 3-14. Ernst & Sohn GmbH und Co. KG. Berlin 2014. ISBN: 978-3-433-03050-9.

[12] EN 16309: 2014 Sustainability of construction works - Assessment of social performance of buildings - Calculation methodology. European Committee for Standardisation.

[13] BREEAM (online). http://www.breeam.org/index.jsp, http://www.breeam.org/about.jsp?id=66, http://www.greenbooklive.com/search/scheme.jsp?id=202 [Accessed on 15. January 2015].

[14] DGNB (online). http://www.dgnb-system.de/de/, http://www.dgnb-system.de/de/projekte/ [Accessed on 13. January 2015].

[15] HQE (online). http://www.behqe.com/, http://www.behqe.com/hqe-in-the-world/cartography-of-projects [Accessed on 15. January 2015].

[16] LEED (online). http://www.usgbc.org/leed, http://www.usgbc.org/projects [Accessed on 15. January 2015].

[17] MINERGIE (online). http://www.minergie.ch/, http://www.minergie.ch/gebaeudeliste.html [Accessed on 15. January 2015].

[18] ÖGNB (online). https://www.oegnb.net/, https://www.oegnb.net/zertifizierte_projekte.htm [Accessed on 13. January 2015].

[19] World Green Building Council (online). [Accessed on 15 January 2015].

[20] Dolezal, F.: Gebäudezertifizierung und nachhaltiges Bauen. Ökostandards in Österreich. Zuschnitt Attachment. proHolz Austria. Vienna 2010.

[21] BREEAM UK New Construction. Technical Manual, SD5076: 2.0, 2014.

[22] DGNB Kriterium TEC1.2 Schallschutz für Neubau Kleine Wohngebäude, 2013.

[23] DGNB Kriterium TEC1.2 Schallschutz für Neubau Wohngebäude, 2012, Upgarde 2013.

[24] DGNB Kriterium TEC1.2 Schallschutz für Neubau Büro- und Verwaltungsgebäude, 2012, Upgrade 2013.

[25] DGNB Kriterium SOC1.3 Akustischer Komfort für Neubau Büro- und Verwaltungsgebäude, 2012, Upgrade 2013.

[26] DEGA (ed.): Schallschutz im Wohnungsbau – Schallschutzausweis. DEGA-Empfehlung 103. Deutsche Gesellschaft für Akustik e.V. Berlin 2009.

[27] HQE Scheme Environmental Performance Non Residential Building. Assessment scheme for the environmental performance of non-residential building under construction – HQE certified by Cerway. 2013.

[28] HQE Assessment Scheme for Environmental Performance of Residential Buildings. Assessment Scheme HQE certified by Cerway for Environmental Performance of Residential Buildings under construction. 2014.

[29] LEED BD-C: Data Centers, v4. Acoustic performance (online). http://www.usgbc.org/node/2614139?return=/credits [Accessed on 15. January 2015].

[30] MINERGIE-ECO Vorgabenkatalog und Umsetzungsanweisungen. Kleine Wohnbauten (2011) – Neubauten, 2014.

[31] MINERGIE-ECO Vorgabenkatalog und Umsetzungsanweisungen. Neubauten, Version 1.2, 2014.

[32] ÖGNB Österreichische Gesellschaft für Nachhaltiges Bauen Wohnbau 2010 W 2.2, 2014.

[33] ÖGNB Österreichische Gesellschaft für Nachhaltiges Bauen Dienstleistungsgebäude 2010 DL 1.3.1.1, 2014.

[34] Birgit Rasmussen & María Machimbarrena (editors), COST Action TU0901 – Towards a common framework in building acoustics throughout Europe. ISBN: 978-84-616-7124-3.

Assessment of warning sound detectability for electric vehicles by outdoor tests

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ABSTRACT

Electric Vehicles (EV) are characterized by a high reduction of the acoustic emission. The absence of warning sounds entails a risk situation for pedestrians. The previous research is focused on detectability of warning sounds in different noise environments. These experiments are performed indoors, where a pedestrian's conditions are not similar to real road crossing. Drivers' behaviour study demonstrated that different environments and workload have influence on reaction time. Consequently, this paper proposes a methodology for the analysis of detectability of real warning sound using a dynamic subject. The sample was composed by 65 participants walking around a pedestrian area. Participants had to react when they detected a vehicle approaching. The subject's response was affected by background noise, therefore, this parameter was measured. The results establish that power levels have influence on the detectability. There is an optimum power level which improves efficiency of vehicle detection. Besides, warning sound features and learning effect, based on previous experience, have influence on subject response.

Keywords: Outdoors experiment, reaction time, warning sound, electric vehicle and background noise.

1. INTRODUCTION

The denominated quiet vehicles, Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) in electric mode, do not have relevant engine and other mechanical noise sources, when these are compared with Internal Combustion Engine vehicles (ICE) [1]. Consequently, EV are less audible at low speeds than ICE [2], [3]. At speeds above 35 km/h, tyre/road and aerodynamic noise predominates over engine noise [4], therefore EV are audible when this limit is exceeded.

Maximum noise level difference between EV and ICE, around 20 dB, is presented in stationary position [5]. Therefore, for slowly approaching, EV are detected at a significantly closer distance than ICE [6]. According to the National Highway Traffic Safety Administration (NHTSA), this level reduction of noise implicates an unsafe situation on the road [7]. For the purpose of reducing the crash risk, EV are going to be provided by warning sound devices.

The absence of warning sounds supposes that pedestrians only obtain the information through their visual field [8]. Consequently, this risk is higher for the unprotected group of people: visually impaired, children, elderly or cyclists. This group cannot perceive the quiet vehicles in the correct security conditions [7], [9], [10]. With these warning sounds, pedestrians would have more information about their surroundings and they could notice the vehicle presence and the driver behaviour, so they could better estimate the traffic risk.

Recently, the European Union has regulated the Acoustic Vehicle Alerting System (AVAS) installation [11]. The minimum overall level in the spectrum and in each octave band are established by this regulation. Particularly, the minimum overall noise level is set at 50 dB(A) to speeds of 10 km/h and 56 dB(A) to 20 km/h. Depending on the speed, this normative suggests a frequency shift. The speed of 20 km/h is established as maximum and the device could be disabled. The United States regulation on AVAS establishes that it will be required at speeds up to 30 km/h. The final American rule do not establish "pitch shifting" to detect the vehicle speed increase. In contrast, it replaces sound modification with noise pressure level increase [12]. The Japanese Ministry of Land, Infrastructure, Transport and Tourism has set the limit to warning sound emission at 20 km/h [13]. According to aforementioned references, EV are not allowed to exceed ICE noise level, for the same vehicle category and operating conditions.

Depending on features, there are two main typologies of previous studies and for both typologies the subject is static. 1) Research developed indoors under low background condition, as interactive evaluation of sound used by Dhammika [14]. 2) The studies emplaced at open space with real background noise. In this way, a pedestrian's acceptability to different sound on a public road was analysed [5]. This research evaluated acceptability by the subject seated when a vehicle was approaching at a speed of 15 km/h. The results demonstrated that sounds had higher acceptability than an engine noise.

The vehicle detectability was analysed at the Emerson's outdoors study, and it implied measurement of background noise [15]. 15 visually impaired people seated on either sides of the road were the study subjects. The experiment was based on the approach of different vehicles (ICE and HEV with warning sound and without it) to pedestrians at a speed of 20 km/h. The vehicle detection distance was determined during the test. The results indicated that warning sounds with a maximum energy at 500 Hz and an amplitude modulation can help to optimize the detectability.

Other studies are developed outdoors to record vehicle pass-by or background noise. Afterwards, the subject test takes place in a controlled room [16-18]. Parizet [16] studied the pedestrian's detection when a car arrives using nine sounds. The subject sampled was shaped by 100 sighted and 53 visually impaired people. The vehicle approached from a distance of 30 m at a speed of 20 km/h. It was for two road conditions, wet and dry. The results established timbre parameters which reduce reaction time. The authors concluded that efficient warning sounds have a low number of harmonics, absence frequency modulation and irregular amplitude modulation. Besides, warning sound audible range was analysed in different environments, as Yamauchi studied [17]. The experiment was characterised by 3 warning sounds, 4 background noises and 31 participants (German and Japanese subjects). The results indicated that environmental conditions and warning sounds have influence on minimum audible level. Poveda [18] examined background noise influence on warning sound detectability and established the risk for pedestrians. This research determined reaction time when a vehicle was approaching. The response of 131 participants was studied using 8 warning sounds and 3 environmental situations. At a speed of 28 km/h, the vehicle approaching was simulated under laboratory conditions. The authors showed the influence of surroundings on warning sound detectability. Reaction time can be affected by sound masking, therefore increasing background noise will decrease the detectability. Researchers concluded that warning sounds similar to ICE vehicle enhance the detectability.

The test typology inside an insulated room is justified by the importance of controlling environmental conditions, it being possible to guarantee prefixed experiment parameters. The static position of the subject presents the incertitude about what would be the response produced by the same subject in a dynamic urban environment. For instance, some conditions of the pedestrian's surroundings are being depreciated during static tests and these could not be extrapolated to real environment. For this reason, it is necessary to study the pedestrian's response under these dynamic test conditions that largely differ from simulated conditions inside an insulated room. Makishita [19] demonstrated the fact that test conditions influence on drivers' reaction time. The research established significant differences between reaction time at a public road and in a simulated city street. According to the study, experiment conditions influence on psychoacoustic behaviour of listeners.

Therefore, the investigation focuses on the following characteristics. The experiment is carried out at a pedestrian area. The subject is walking and carrying the equipment. Background noise is measured during the experiment. The signals simulate a vehicle approaching at a speed of 30 km/h. During auditory test each sound is presented at 3 sound levels.

Prime objectives have been identified as: 1) determing background noise influence on detectability, 2) comparing efficiency of different warning sound to reduce pedestrian's risk [20-22] and 3) defining subject's behaviour with respect to warning sound noise level. The goal of the present study is to improve EV auditory detectability, but limit noise pollution generated by this source.

2. METHODOLOGY

The experiment evaluated the audibility of EV on street-crossing simulation. The subjects were tested outdoors and background noise was recorded. They perceived warning stimuli through headphones while they were walking. More details about the research method are provided in the subsequent sections.

2.1. Sound stimuli

Different warning sounds were extracted from bibliographic references [20-22]. Signal sounds used for the tests were selected as all of them allowed evaluation in similar test conditions. Consequently, the following conditions were established as criteria choice: frequency content of sounds should not present relevant changes over time, audio files should not include background noise and should be considered same motion condition, namely stationary vehicle.

To select warning sounds, those which had opposite results of annoyance and suitability were considered, according to Delta Senselab evaluation. Warning stimuli considered as slightly annoying were: “Q4noise”, “Jet4low” and “Low Friction”. Other two signals included in this study as moderately and highly annoying were: ”Motorgear” and “N-Clean”.

During warning sound design, the frequency was considered to improve efficiency. All these signals concentrated their energy at the optimal frequency range between 100 and 2000 Hz, as shown in Fig. 1.

The “Jet4low” concentrated the energy on the low frequency range, specifically between the interval of 100 to 1000 Hz. This sound presented a predominant contribution near the band of 250 Hz, with regard to remaining octave frequency bands.

“Low Friction” signal was characterized by having a reference frequency around 300 Hz, although lower frequencies included an important energy concentration until 100 Hz. This stimulus showed a larger energy distribution for the different spectrum frequencies, when it was compared with other acoustic signals.

Energy was concentrated at low frequencies in the signal “Motorgear” in the range of frequencies from 100 to 500 Hz. At the same time, different harmonics nearby the frequencies of 700, 1000, 1300 and 1600 Hz were contained on the spectrogram.

The energy in “N-Clean” signal was located predominantly at frequencies 125 Hz and 250 Hz, but it also showed the energy density distribution at the spectrum until 4000 Hz.

“Q4noise” sound was characterized by having higher energy density at low frequencies, in the interval between 250 Hz and 500 Hz. Furthermore, this stimulus presented alternative peaks around 200 and 300 Hz.

At the European regulation [23] the limitation for the sound level generated by the AVAS was determined. In this way, EV could not overtake the ICE sound levels included in the same category (M1) operating under the same conditions. That limitation was considered during the tests.

For this reason, the sound power level of a light vehicle with an ICE was quantified using the “Mèthode de Prévision du Bruit des ROUTES - NMPB” [24]. This French model was established to consider the noise produced by traffic flow. Sound power level produced by a model vehicle was established at 92 dB(A). This value was extracted by extrapolating Pass-by model for traffic flow to individual motion vehicle and setting estimated operating conditions. Vehicle motion was

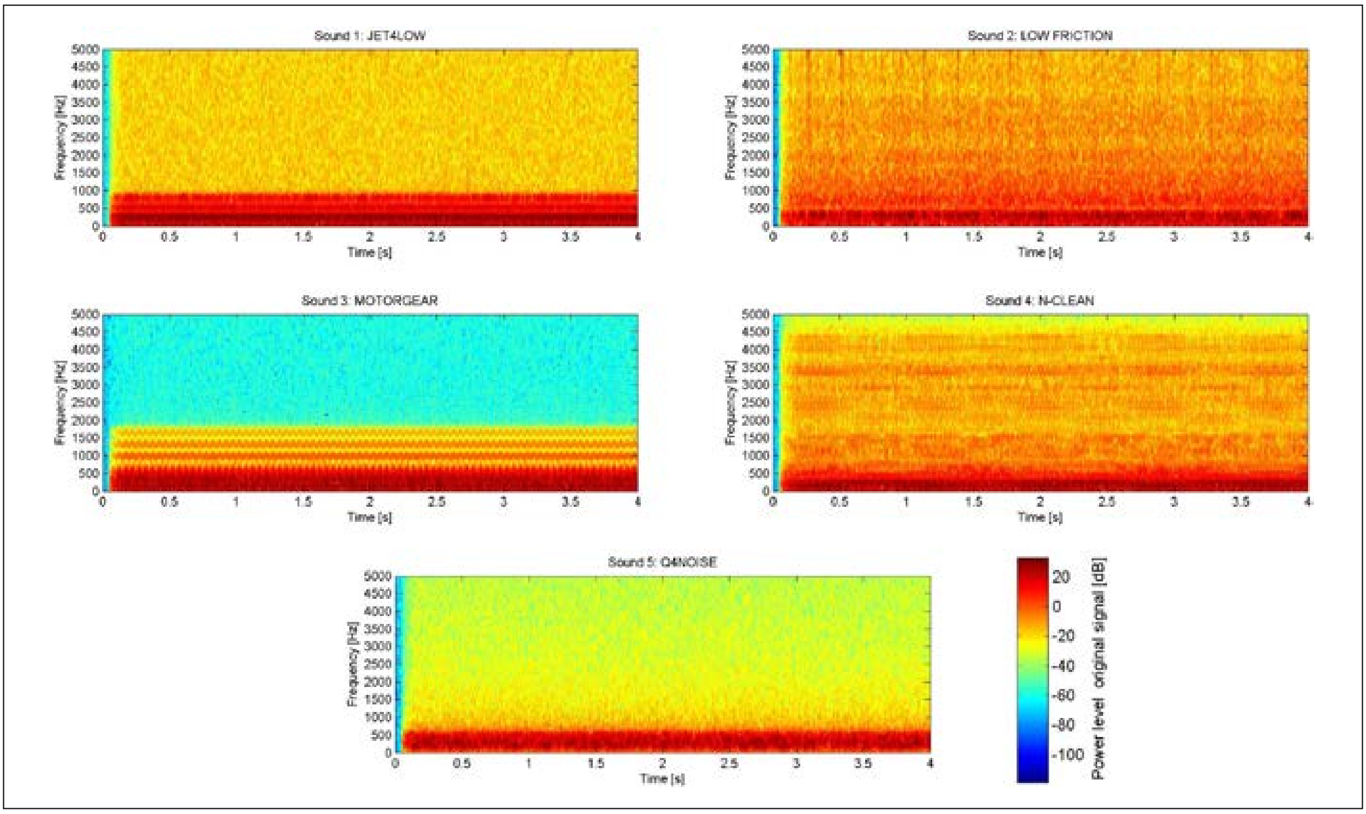

Figure 1. Spectrogram of the different warning sound signals used during the tests.

simulated at a constant speed of 30 km/h on an intermediate asphalt R2 [24]. In the R2 asphalts category BBTM 0/10 type 1, BBSG 0/10, ECF, BBUM 0/10 surfaces were included.

A pedestrian was positioned 2 m from the centre of the vehicle (minimum distance between subject and car) and EV was located at a 30 metre distance from ahead of the subject, according to Fig. 2. Under these speed and distance conditions was established the recording length.

The possibility of reducing road traffic noise level was analysed through source noise reduction. Consequently, a pair of sound power levels were established at 85 and 75 dB(A). These were considered below 92 dB(A) limit, justified by the fact that these warning sounds were designed to be more efficient than ICE sound. This estimation was considered to analyze the relevance of the sound power level into detectability of each signal. At the same time that the signals could reduce reaction time with a lower sound power level, these could reduce pollution and increase pedestrian safety in cities. Hence, five warning sounds were used in the study, each of them for three power levels.

Audio recording of warning sound was processed to simulated the Pass-by of a vehicle provided with an AVAS, it was considered circulating at a steady speed. Also, the pressure level attenuation by distance and Interaural Time Difference (ITD) was considered. The peak pressure levels issued by the vehicle were set at 78, 71 and 61 dB(A) depending on the power level considered, as it is represented in Fig. 3.

Between output signal and the real stimulus there were not a linearly related, due to the fact that input impulse in the frequency spectrum was modified by the response emitted. This effect produced by the headphones was corrected by impulse response inverse filter.

2.2. Instruments setup

The subjects carried different elements to allow execution, control and registration, while they were walking around the area. This situation implied that experimental setup should be lightweight and easily transported. These devices were a laptop inside of a shoulder bag, a microphone, headphones and a push-button.

The real background noise was acquired in auditory test by means of a microphone. On the one hand, environmental noise recorded in the area showed if there were anomalous tests. As well, the background noise level during the experiment was measured.

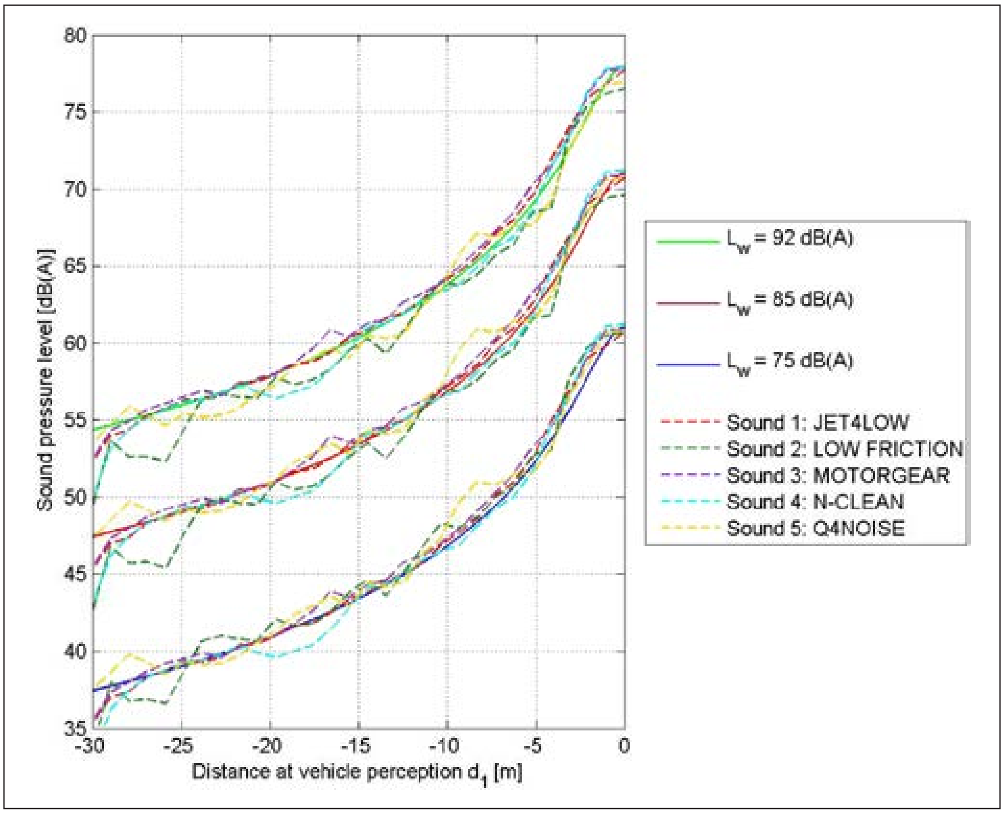

Figure 2. *Schematic representation of the investigated Pass-by condition.*

The laptop was used as a government element, allowing the process control and recording the parameters. The subject transmitted his or her response to stimulus through the push-button and then these data were sent to recording device. Headphones were used to simulate the sound of approaching vehicle, according to Fig 4.

2.3. Procedure

All tests were developed in the same pedestrian zone, in order to ensure the same conditions for each listening test and minimize environmental influences. The area was composed by concrete sidewalk and some ground plots with ornamental trees, flowers and grass, as shown in Fig. 5. The background noise was low with few human disturbances, allowing to diminish the presence of invalid subjective test (anomalous measures).

During the test, subjects were walking around the area. Acoustic stimuli were presented in random order and sequence was different for each subject. Time interval between warning sound was variable. Test simulated a vehicle provided with a warning sound when it was approaching to a subject, as it is shown in Fig. 2.

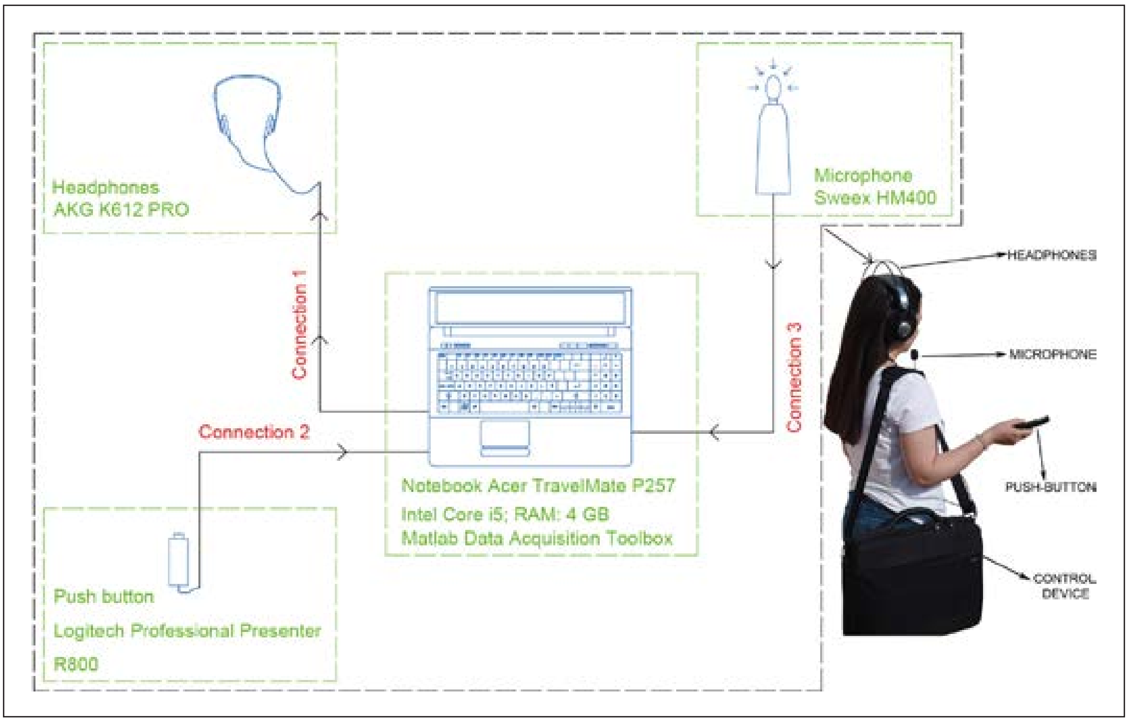

Figure 3. *Pressure level as function of the approaching to pedestrian.*

Figure 4. *Essay setup.*

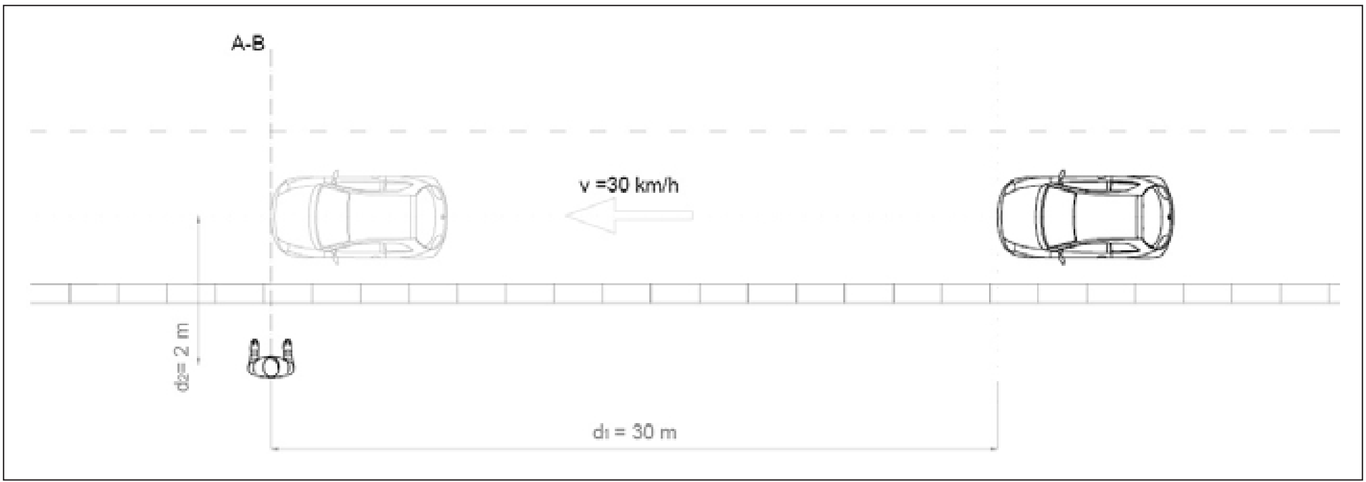

Figure 5. General views of the test location.

Some disturbing sounds were added to the signal, such as those made by a tweeting bird or a barking dog. Since the study also took into account the association between sound stimulus and the presence of vehicle, the disturbing sounds eliminated the possibility that the subject impulsively reacted to any environmental sound, therefore sound was always related to noise source.

Road-crossing was explained to the participants, they had to detect a vehicle arriving to them. When warning sound stimulus was associated with a vehicle, subjects had to record their response in the shortest possible time. If the stimulus was associated with environmental source, subject should not react. Response time depends on the perception time and the association time.

2.4. Background noises

The experiment was developed outdoors and different sounds were presented to subjects using the open headphones AKG K612 PRO. For this reason, each test was conditioned by different background noise produced at the environment.

During the auditory test, the subject received two background noise, first of them was a pink noise and the second one was a real environmental noise. The standardized background noise was applied for two purposes, to guarantee a minimum background noise level and to avoid the annoyance caused by eardrum vibration when the ears were covered by headphones.

The pink noise was added by the headphones to real background noise. This normalized noise was implemented with an equivalent sound pressure level of 37 dB(A). That result was extracted considering vehicle simulation conditions. The minimum sound pressure level produced by a EV equipped with AVAS was established at 75 dB(A) for a 30 m distance to pedestrian, it is presented at Fig. 3.

2.5. Subjects

In the study participated 65 subjects, comprising 50 males and 15 females aged between 16 to 58 years old. None of them reported any hearing impairment.

Through post-test analysis were excluded non-valid subjects due to presence of impulsive reaction to environmental noise or anomalous background noise measurements. 10 subjects were discarded. Finally, 55 listeners took part in the study, comprising 41 males and 14 females.

3. RESULTS

3.1. Effect of background noise on reaction time

The background noise is used to consider the circumstances surrounding the subject during auditory test. The acoustical environment was considered as the equivalent continuous background noise level (L_{Aeq}). This parameter was measured using fast time weighting. Testing period was established between the beginning of the pass-by simulation and the moment when subject responded.

Fig. 6 shows the reaction time recorded by subjects as response to the stimuli during the experiment. The subjects who did not react within the established time interval for the approaching vehicle are not represented, this part of the sample is considered in Fig. 7 and 8.

The five warning stimuli are presented at different sound levels, these are shown using points markers: green, blue and red. Different power levels of warning sound were independently analyzed, however results showed that sample behaviour tended to be similar. As it is observed in Fig. 6, the reaction time of the sample tends to increase when background noise is louder, this means that the listeners need a higher time interval for their reaction. Moreover, comparing power levels is possible to establish that the subject takes longer to produce his or her response when this parameter is lower.

Background noise levels were analysed for different reference levels, as is presented in Table 1. Noise recorded during auditory test were characterized using statistical descriptors. Independent measures were established using three separate samples that gave the same results, the mean valour was around 50 dB(A) and standard deviation was approximately 5 dB(A). The results showed that these parameters did not present considerable differences for the different power levels.

Reaction time statistics are shown separately for each power level of warning stimuli in Table 2. Reaction time difference between intermediate reference level and the low one was 0.82 s. On the other hand, reaction time between higher and intermediate levels tended to be reduced, being the difference of 0.18 s in absolute terms. No significant differences in response between higher and intermediate level were detected. However,

Table 1. Statistical parameters for background noise recorded in auditory test.

Reference level [dB(A)]	92	85	75
Mean [dB(A)]	50.36	50.03	50.26
Standard Deviation [dB(A)]	5.01	4.96	4.90

Table 2. Statistical parameters for reaction time by power level.

Reference level [dB(A)]	92	85	75
Mean [s]	1.61	1.79	2.61
Standard Deviation [s]	0.93	0.94	0.96

low level made that subjects' response to warning sound were slower. Standard deviation of reference levels was around 1 second.

This comparative shows that all different power levels were evaluated under the same environmental conditions. Nevertheless, the reaction times suggested that subjects required less time to response when warning sound increased. Being possible to establish that there is a relationship between reaction time and power level of the warning sounds.

3.2. Comparison of auditory reaction time and levels

As explained in the previous subsection 3.1, all warning sounds were presented to the subjects under similar background noise. Auditory tests of all subjects were carried out in pedestrian zone and mean of background levels were presented on the same order independently

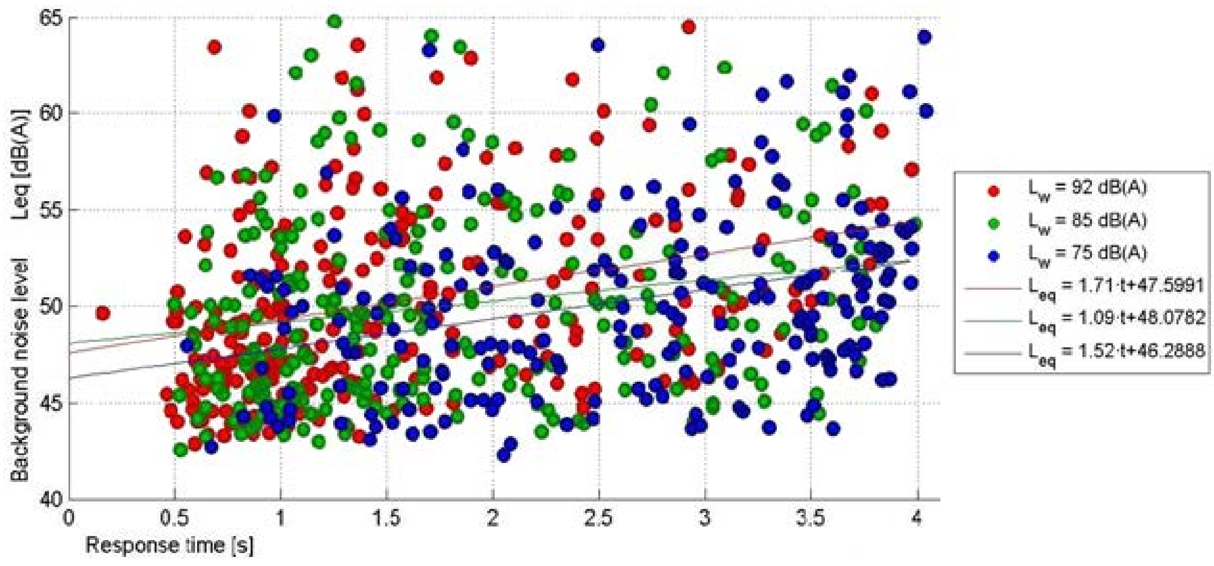

Figure 6. Reaction time to vehicle as function of background amb ient noise level and sound power level.

for each sample (see Table 1). Therefore, this subsection analyzes participants' responses, without taking into account background noise. Fig. 7 shows the distribution of sample percentile response time depending on three reference levels. To obtain these reaction time distributions for each power level, the 5 warning stimuli were considered.

As can be seen in Fig. 7, the 50th percentile reaction time of the intermediate power level was 1.6 s. However, reaction time was 3.12 s when warning stimuli was presented at low power level. The difference in the reaction time percentile between these reference levels was 1.52 s. The response percentile indicates that interval time increase notably by the low power level signal.

Response difference was presented in all percentile ranges. This reaction time gaps between the low and the intermediate levels were 0.93 and 1.11 s, for 25th and 75th percentiles respectively. Hence, time interval is reduced around 1 s, but it continues being relevant. As can be determined through the intermediate and the low power level, reaction time tends to reduce when source level increases.

Related to the previous paragraph, the 80% of the subject sample reacted to the warning stimuli before 4 s for the low power level. In contrast, the 95% of the subjects detected the vehicle before 4 s at the intermediate. This sample behaviour revealed that this power level of 85 dB(A) improved the detectability more than 75 dB(A) in the same environment.

On the other hand, similar response distributions were observed between the higher and the intermediate power levels. This comparative showed that the subjects' response converged to similar reaction times. Owing to the maximum difference reaction time was 0.24 s (75th percentile) and minimum difference was 0.13 s (25th percentile). However, the source noise level increase of 7dB(A) is relevant considering the vehicle accumulation in cities. This situation implicates a noise rise that is not justified by the short detectability difference between both levels. Summarising, the results show that the optimum warning sound level is 85 dB(A).

3.3. Evaluation of warning-sound at optimum level

The optimum power level is established at 85 dB(A) derived from the analysis developed at the subsection 3.2. Consequently, it is possible to achieve good levels of detectability without compromising the acoustical environment. For the power level of 85 dB (A), the responses to the different warning signals are analysed, as can be seen in Fig. 8.

During the test, eight subjects did not react in response to "Q4noise" signal, these non-response participants

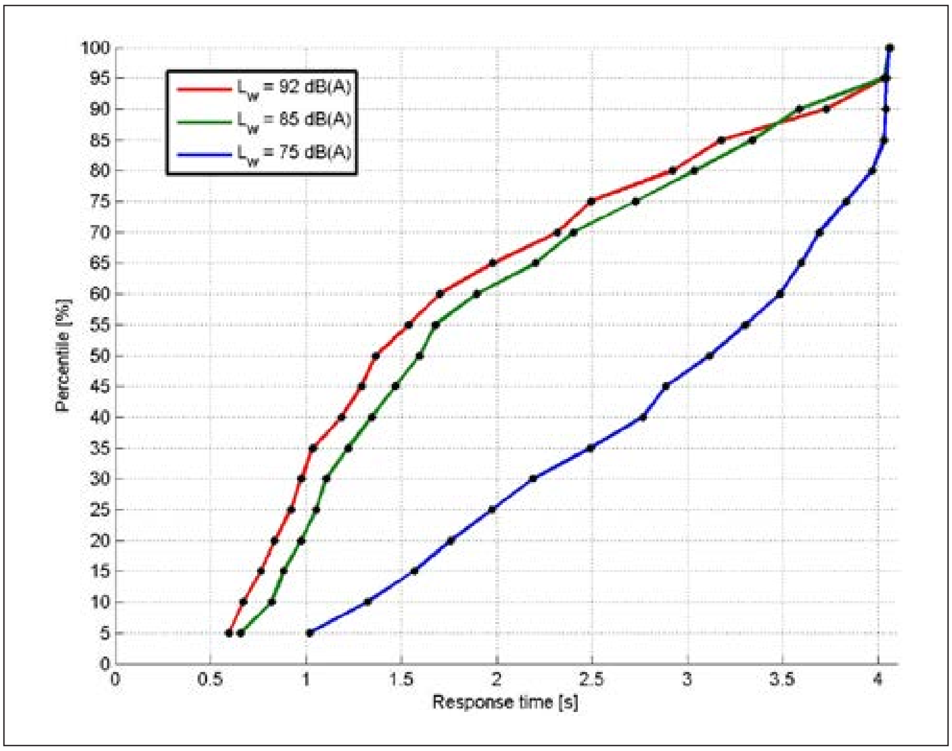

Figure 7. Distribution of response time with different sound power levels.

represented a relevant percentile around 10%. Comparing the subjects' responses, it is possible to know that "Q4noise" presented more adverse responses than others used signals. This fact indicated that this warning signal presents a low association with a road vehicle.

"Low Friction" was the second stimulus with slow participant response times. Similar behaviour than "N-Clean" and "Jet4Low" signals. Despite this, the trend showed that "N-Clean" was more detectable than "Jet4Low", as is presented in Fig. 8.

Finally, the most efficient warning sound was "Motogear", it was probably justified because this sound simulated ICE sound. The reaction time is influenced by the time period between the beginning of the approach vehicle simulation and the sound identification. Due to this fact, "Motorgear" sound presented a reduction on the time interval required by pedestrians.

Significant differences were presented between reaction time of "Motorgear" and "Q4noise", the most efficient and inefficient, respectively. For the 50th percentile, time gap between both warning sounds was 0.52 s. However, 2.04 s was the response time needed by subjects to react to "LowFriction" at 50th percentile while "Motorgear" presented a time of 1.30 s. Consequently, the difference between them was 0.74 s.

The analysis determines that pedestrians' behaviour is influenced by warning sounds features. By means of outdoors experiment, it is possible to determine that the warning stimuli that is closely associated with a road vehicle shows an earlier response.

4. CONCLUSION

The present paper proposes an alternative dynamic pedestrian test carried out outdoors, instead of the current indoor test. The laboratory test improves the control of variables, however the subject's surrounding are less similar to urban environments. The pedestrian's behaviour was evaluated in similar real conditions thanks to the proposed test using more parameters than the laboratory test.

The experiment was developed in a quiet area and a wide sample of 55 subjects was taken into account in order to control disturbance on parameters. Background noise was recorded to analyse the influence on response for each subject. During the test, it simulated an approaching vehicle at a speed of 30 km/h from 30 m while the pedestrians were walking.

Study results show that it is possible to establish a relationship between power sound level and reaction time, when warning sound increases the pedestrian's response time decreases. This trend is presented for warning sound power under the level established as

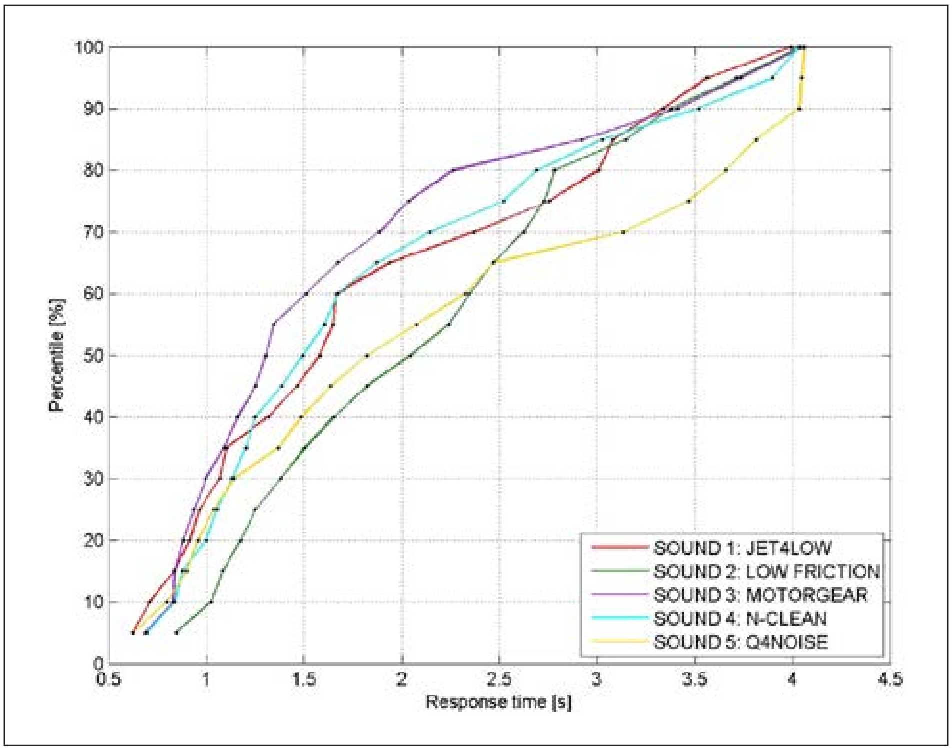

Figure 8. Distribution of response times with different warning sounds at same power level of 85 dB(A).

optimum, from this value the detectability is the same order and shows independent behaviour of the power signal.

The optimum power level is 85 dB(A) under experiment conditions. The optimum is justified because a higher level does not improve pedestrian safety, since auditory detectability is similar as shown in Fig. 7. However, this increase produces a significant growth in noise pollution in urban areas where the number of vehicles are high.

The results prove the influence of background noise on detectability, and it has been shown that when raising the background noise the reaction time increases. Hence, the safety conditions are reduced at the same power level. This relation is consistent with previous research developed indoors [17], when the subject does not walk and does not interact with the surroundings.

Statistical distribution shows the contribution of each sound to improve the detectability. The warning sounds are ranked based on their efficiency in the following order: “Motorgear”, “N-Clean”, “Jet4Low”, “Low Friction” and “Q4noise”, grouped from the more easily detected signal to less efficient sound. “Motorgear” is more efficient sound than the other analysed signals, this fact is probably justified by the influence of previous experience. “Motogear” sound simulates ICE, which is associated with a vehicle coming more quickly. Consequently, reaction time is significantly lower for this warning signal. Similar conclusion is presented in other studies [18], [25] using different stimuli and indoor exposure.

The study presents limitations with respect to the control experiment, increasing the incertitude of measurement. In contrast, the control of parameters is guaranteed during indoor experiment. Consequently, the present methodology is proposed as a complementary study that would validate results in a controlled environment through conditions similar to reality. These experiments would allow a comparative analysis between qualitative test (real pedestrian behaviour) and quantitative test (quality control of measurement).

REFERENCES

[1] Campello H., Peral R., Campillo N., Velasco E. The effect of electric vehicles on urban noise maps. Applied Acoustics, Vol 116, pp 59-64. September 2016.

[2] Grosse J., Weber R., Van de Par S. Comparison of detection threshold measurements and modelling for approaching electric cars and conventional cars presented in traffic and pink noise. ICA 2013, Montréal, Session 5aPP. June 2013.

[3] Minimum Sound Requirements for Hybrid and Electric Vehicles. Docket Number NHTSA-2011-0100. Washington, DC. National Highway Traffic Safety Administration (2013).

[4] Sandberg U., Ejsmont J.A. Tyre/road noise reference book. Informex, Harg SE-59040, Sweden, Kisa 2002.

[5] Japan Automobile Standards Internationalization Center, JASIC. A Study on Approach Warning Systems for hybrid vehicle in motor mode. Presented at the 49th World Forum for Harmonization of Vehicle Regulation (WP.29) Working Group on Noise (GRB)-49 (2009). Document number: GRB-49-10.

[6] Altinsoy E. The detectability of conventional, hybrid and electric vehicle sounds by sighted, visually impaired and blind pedestrians, Proceedings of the 42nd Inter-Noise, Innsbruck 2013.

[7] Wu J., Austin R., Chen C-L. Incidence Rates of Pedestrian and Bicyclist Crashes by Hybrid Electric Passenger Vehicles: An Update. (DOT HS 811 526). Washington, DC: National Highway Traffic Safety Administration. October 2011.

[8] Kaltwasser H. EBU’s Work on Silent Vehicles and VI Pedestrian. eVADER project: Electric Vehicle Alert for Detection and Emergency Response project. November 2013.

[9] Guth D., Ashmead D., Long R., Wall R., Ponchillia P. Blind and Sighted Pedestrians’ Judgments of Gaps in Traffic at Roundabouts. Human Factors: The Journal of the Human Factors and Ergonomics Society. Volume 47, Issue 2. June 2005.

[10] Hanna R. Incidence of Pedestrians and Bicyclist Crashes by Hybrid Electric Passenger Vehicles: National Center for Statistical Analysis Technical Report. DOT HS 811 204 Washington, DC: National Highway Traffic Safety Administration. September 2009.

[11] Regulation (EU) Nº 138/2017 of the Economic Commisision for Europe of the United Nations – Uniform provisions concerning the approval of Quiet Road Transport Vehicles with regard to their reduced audibility.

[12] Minimum Sound Requirements for Hybrid and Electric Vehicles. National Highway Traffic Safety Administration; Federal Motor Vehicle Safety Standards Nº 141. November 2016.

[13] Ministry of Land, Infrastructure, Transport and Tourism. Japanese Activities on Approaching Vehicle Audible System for HEVs and EVs. May 2010.

[14] Dhammika W. Using interactive simulation for EV sound evaluation. eVADER projec: Electric Vehicle Alert for Detection and Emergency Response project. November 2013.

[15] Wall Emerson R., Kim D., Naghshineh K., Pliskow J., Myers K. Detection of quiet vehicles by blind pedestrians. Journal Transportation Engineering, Vol 139, Issue 1, pp 50-56. January 2013.

[16] Parizet E., Ellermeier E., Robart R. Auditory warnings for electric vehicles: Detectability in normal-vision and visually-impaired listeners. Applied Acoustics, Vol 86, pp 50-58. December 2014.

[17] Yamauchi K., Menzel D., Fastl H., Takada M. Psychoacoustic examination of feasible level of additional warning sound for Quiet Vehicles. Acoustical Science and Technology, Vol 36, No 2, pp 120-125. December 2014.

[18] Poveda P., Peral R., Campillo N., Nescolarde J., LLoret M., Ramis J. Study of the effectiveness of electric vehicle warning sounds depending on the urban environment. Applied Acoustics, Vol 116, pp 317-328. October 2016.

[19] Makishita H., Matsunaga K. Differences of drivers' reaction times according to age and mental workload. Accident Analysis and Prevention. Vol 40, Issue 2, pp 567-575, March 2008.

[20] Delta SenseLab. Report: Audibility test of exterior warning signals for electric cars. Denmark 2010.

[21] Delta SenseLab. Report: White paper on external warning sounds for electric cars - Recommendations and guidelines. Working Group on Noise (GRB) Informal group on Quiet Road Transport Vehicles (QRTV) Working papers of the 6th informal meeting. Documents number: QRTV-06-04. May 2011.

[22] Delta SenseLab. Ectunes. Sonic Minds. Report: Warning sound samples. Working Group on Noise (GRB) Informal group on Quiet Road Transport Vehicles (QRTV) Working papers of the 6th informal meeting. Documents number: QRTV-06-07. March 2011.

[23] Regulation (EU) Nº 540/2014 of the European Parliament and of the Council of 16 April 2014 on the sound level of motor vehicles and of replacement silencing systems.

[24] French method for road traffic noise prediction "NMPB-Routes-1996 and 2008 (SETRA-CERTULCPC- CSTB)", and french standard "XPS 31-133".

[25] Misdariis N., Gruson A., Susini P. Detectability study of warning signals in urban background noises: a first step for designing the sound of electric vehicles. In: Proc. ICA 2013, Montréal 2013.

A list of sound scattering coefficients of bulky objects and people in industrial workplaces

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ABSTRACT

Furniture (desks, chairs, etc.), people and walls with irregular surfaces present in workplaces are often sources of sound scattering. Predictive software applications like Ray+ used to map acoustic pressure in the workplace use acoustic characteristics such as the absorption and scattering of walls and furniture. Here, we use a measurement system designed to determine the sound scattering coefficient of bulky objects in situ. The measurement technique is based on the method initially developed by Vorländer and Mommertz under free-field conditions. To overcome problems of parasite echoes from the reverberation of other walls of the building and sources of noise present on the site, we use a dedicated emission/reception system using multipolar weightings to spatially filter parasite echoes, and an impulsive sound source that, combined with a large time window, allows adequate separation of the different signals received by the array as a function of time. The measurement of the sound scattering coefficient in an office of one or more persons, cabinets or panels containing one. was performed for several angles of incidence and in a noisy work environment. The results permit building an initial database of sound scattering coefficients per 1/3octave of office furniture and persons in their work environment.

1. INTRODUCTION

Acoustic software applications like RAY+ [1, 2], developed and used by the National Research and Safety Institute (INRS), require knowledge of average sound reflection coefficients associated with each wall of the workplace, and the objects and people that occupy it, in order to predict sound levels inside them.

Industrial workplaces often contain bulky objects such as furniture (cabinets, chairs, desks, etc.), noisy machines, and employees. Walls made of corrugated sheet steel or perforated cladding, which delimit areas within workplaces, may also have irregular surfaces that can be considered as periodic or aperiodic. These volumes and irregular surfaces generate acoustic scattering and the objective of this work is to establish a list of sound scattering coefficients for these structures.

This list was compiled using an acoustic diffusion measurement device developed by M. Ducourneau [3, 4]. The principle of the measurement is based on the method of M. Vorländer and E. Mommertz [5] originally developed under free-field conditions. This method is based on a process of averaging the acoustic pressure reflected above the diffusive structure to determine the specular reflectance. This method was adapted, tested and validated to measure the sound scattering coefficient of wall facings on an industrial site, i.e. under reverberating conditions and in the presence of powerful sound sources liable to disturb the measurement [6]. An acoustic array developed during previous studies [7] is used to spatially filter echoes generated by the reverberation and those stemming from these sources.

This system was validated in a semi-anechoic environment and then proved efficient for performing this type of measurement in a reverberating workplace [6]. The aim of the work presented here is to determine the sound scattering coefficient of bulky objects present in a workshop in order to build the first scattering coefficient database that can be used for preliminary acoustic calculations of workplaces. Although the measurement system overcomes the problem of reflections, the measurements were performed in a semi-anechoic chamber to obtain the best precision possible.

2. MEASUREMENT OF THE SOUND SCATTERING COEFFICIENT

2.1. *Definition of the sound scattering coefficient*

Sound scattering can be studied for several incidences of the sound field insonifying an irregular surface. For each incidence, there is a reflection zone known as specular, defined as the region of space (or solid angle) where the image source obtained by the reflection is visible through the scattering surface. The most common definition of the scattering coefficient δ is the ratio of the energy reflected towards the exterior of the specular zone to the total reflected energy:

$$\delta = 1 - \frac{\int_{\Omega_S} E(\Omega)d\Omega}{\int_{\Omega} E(\Omega)d\Omega} \tag{1}$$

with Ω_S, being the solid angle corresponding to the area of the reflected specular energy and Ω, the solid angle corresponding to all the reflected energy.

2.2. Method used to measure the free-field sound scattering coefficient

The measurement method developed originally by Vorländer and Mommertz [5] specifies that the source (loudspeaker) and receiver (microphone) must be placed in the far field in the specular direction θ_s. A rotating plate on which the sample with an irregular surface is placed makes it possible to perform measurements for multiple orientations as a function of angle φ.

Figure 3 shows an example of the reflected impulses obtained for three orientations of the scattering surface.

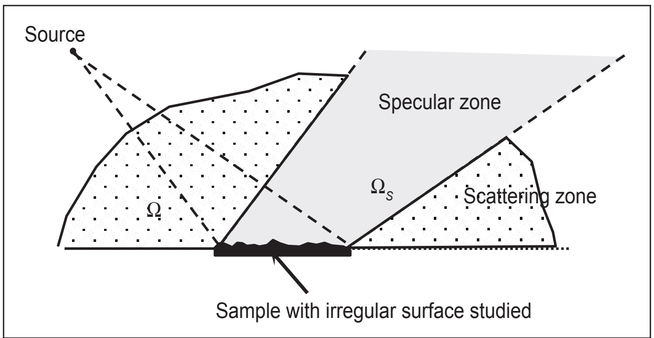

Figure 1. Illustration of the specular and scattering zone.

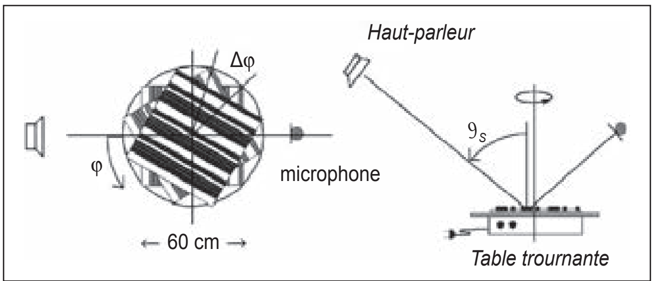

Figure 2. Principle of the method for determining the free-field scattering coefficient [5].

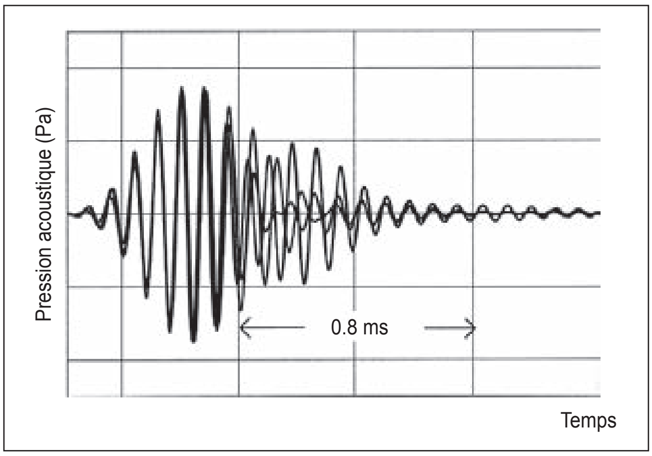

Figure 3. Reflected impulses for 3 different orientations of a wall with an irregular surface [5].

The incident signal is a burst centred on the 10 kHz 1/3 octave.

As can be seen in this figure, the initial part of the impulse response is consistent (in phase) while the remaining temporal pattern shows that these same impulses are no longer in phase. This second part of each impulsive response is therefore attributed to the non-specular component. For a specular angle of incidence θ_s of the source and the receiver and an orientation φ_i, the reflected acoustic pressures $p_{r,\varphi_i}(t,\theta_s)$ can be written as the overlap of a scattering $p_{diff,\varphi_i}(t,\theta_s)$ and specular $p_{spec}(t,\theta_s)$ component:

$$p_{r,\varphi_i}(t,\theta_s) = p_{spec}(t,\theta_s) + p_{diff,\varphi_i}(t,\theta_s) \tag{2}$$

The specular sound pressure is obtained by averaging a large number of reflected sound pressures according to angle φ: it is considered that the specular component remains consistent as a function of φ, contrary to the scattering component which, once averaged, is attenuated:

$$p_{spec}(t,\theta_s) \cong \frac{1}{n}\sum_{i=1}^{n} p_{r,\varphi_i}(t,\theta_s) \tag{3}$$

Under far-field conditions, the total averaged reflected energy in the specular direction θ_s can be written as a function of the Fourier transforms $p_{r,i}(f,\theta_s)$ of the temporal sound pressures measured:

$$E_{tot}(f,\theta_s) = K(f,\theta_s).\frac{1}{n}\sum_{i=1}^{n}\left|p_{r,i}(f,\theta_s)\right|^2 \tag{4}$$

where $K(f,\ \theta_s)$ is a constant dependent on the sound power of the source and on the geometrical positions of the source and the receiver. The specular reflected energy is also proportional to the square of the modulus of the Fourier transform of the specular sound pressure:

$$E_{spec}(f,\theta_s) = K(f,\theta_s).\left|p_{spec}(f,\theta_s)\right|^2 \quad (5)$$

By combining equations (3), (4) and (5), we obtain a sound scattering coefficient in the specular direction θ_s:

$$\delta(f,\theta_s) = \frac{\overbrace{\sum_{i=1}^{n}\left|p_{r,i}(f,\theta_s)\right|^2}^{\text{Energie réfléchie totale}} - \overbrace{\frac{1}{n}\left|\sum_{i=1}^{n}p_{r,i}(f,\theta_s)\right|^2}^{\text{Energie réfléchie spéculaire}}}{\underbrace{\sum_{i=1}^{n}\left|p_{r,i}(f,\theta_s)\right|^2}_{\text{Energie réfléchie totale}}} \quad (6)$$

with n >> 1

From these different scattering coefficients, it is possible to deduce the random-incidence scattering coefficient by integration in the upper half space:

$$\delta(f) = \int_0^{\pi/2} \delta(f,\theta_s)\sin(2\theta_s)d\theta_s \quad (7)$$

In order to use this measurement method under unfavourable acoustic conditions such as those found in workshops (semi-reverberating conditions in the presence of possibly very noisy sources), we replaced the receiver microphone with a directive antenna and the source with an impulsive source. The spatial filtering properties of the antenna and the very brief emission of the source impulse peaks eliminated the parasite echoes from the other walls in the workplace and permitted the temporal windowing of those from the scattering reflection of the unevenly surfaced wall studied.

2.3. Multipolar antenna and impulsive sound source

The impulsive source was designed on the basis of the reverse response of an emission system [6]. This reverse filtering technique was used to calculate the source signal required to equalise the response of the emission system in order to emit short impulses. The emission system contains an equaliser (Yamaha Graphic Equaliser GQ 1031 BII), a power amplifier (APK 2000) and a loudspeaker 10 cm in diameter (Pioneer TS E1077). The transfer function H(f) of the emission system was measured under free-field conditions with an MLS signal as the source signal. Once filtered by the reverse impulse response of the emission system and emitted at the input of the emission system, it produces a very short impulse at

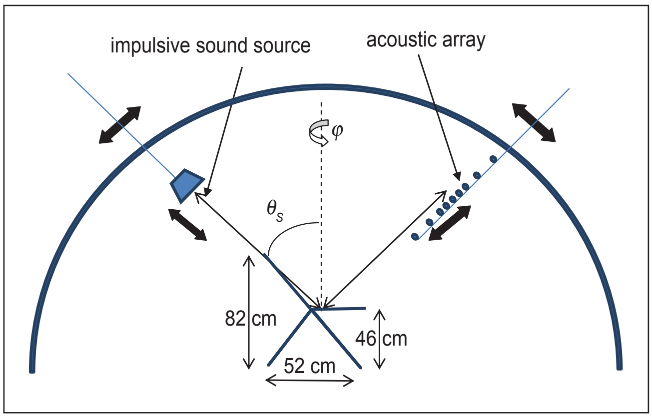

Figure 4. Schematic view of the principle of the measurement system.

the output. It must be emphasised that the reverse impulse response of the emission system must remain at low level at low frequencies as the loudspeaker cannot radiate sound energy in this frequency domain. It was therefore necessary to use a high pass filter (cut-off frequency set at 100 Hz) to avoid the destruction of the loudspeaker.

The receiving antenna used contained 13 sensors and has constant directivity in frequency. The weighting used is multipolar so it is possible to obtain directivities with the narrow main lobe constant in frequency, and attenuations of the secondary lobes reaching 30 dB. The receiver system contains 4 sub-antennae that each use 5 of the 13 sensors spaced by multiples of 2.5 cm [7].

The emission and reception systems (source + antenna) are placed on a frame. The latter can be moved easily around the central axis of the scattering surface studied in order to perform acquisitions as a function of φ.

3. MEASUREMENT OF SOUND SCATTERING COEFFICIENTS

3.1. The bulky objects studied

The different bulky objects studied are:

– Config. 1: a cabinet,
– Config. 2: a table,
– Config. 3: a chair,
– Config. 4: a table + three chairs,
– Config. 5: a table + three chairs + computer,
– Config. 6: a person,
– Config. 7: four chairs,
– Config. 8: four people.

These volumes have different shapes and the aim was to compare the scattering coefficient of one configuration (e.g., one person) with the scattering coefficient of the same configuration augmented (e.g., 4 people). Other examples included a chair compared with four chairs, a table with a table + three chairs + a computer.

A few of the results are presented in the following figures.

Figure 5 shows the experimental set-up for measuring the sound scattering coefficient of a person seated with a volume of 134 × 72 × 62 cm³. The measurement was performed for θ_S angles between 30° and 80° by steps of 10°.

For the "one person" configuration, the scattering coefficient is significant from the 3 kHz octave upwards, with the maximum being reached for angle $\theta_s = 10°$ at $f = 5$ kHz. For the "4-people" configuration (figure 8), the scattering coefficient is significant earlier, from the 500 Hz octave upwards, with the maximum (~ 0.9) being reached for angle 10°.

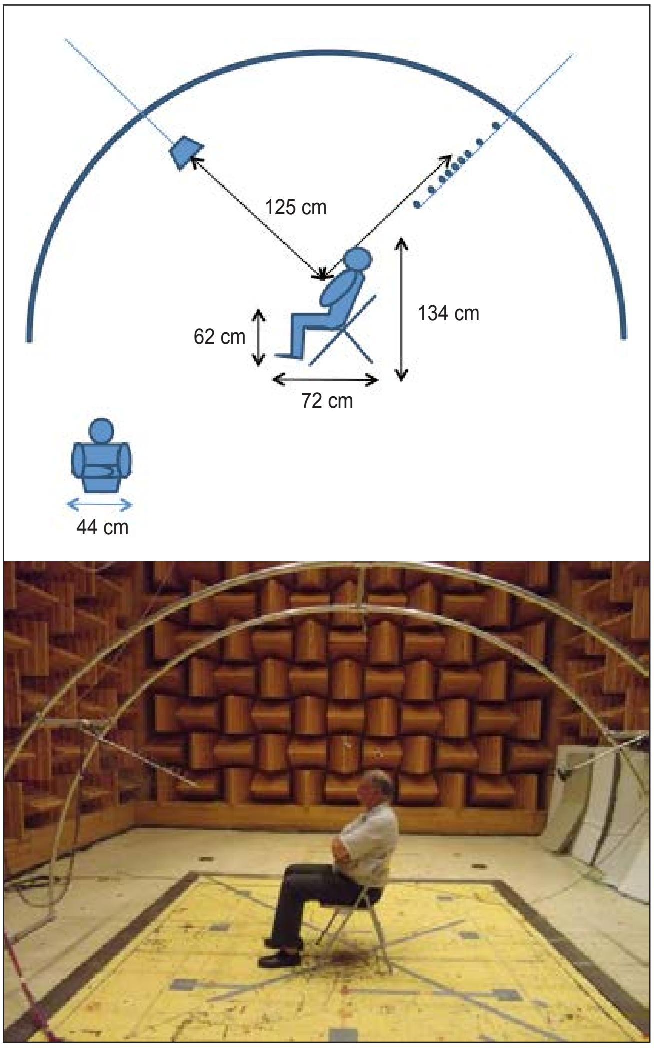

Figure 5. Experimental set-up for measuring the scattering coefficient of one person.

Figure 9 presents the comparison between the sound scattering coefficient obtained for one person and for four people for incidence angles 40°, 50° and 60°. We observed that the more the number of people increases, the higher the scattering coefficient. This may stem from the tortuosity and thus complexity of

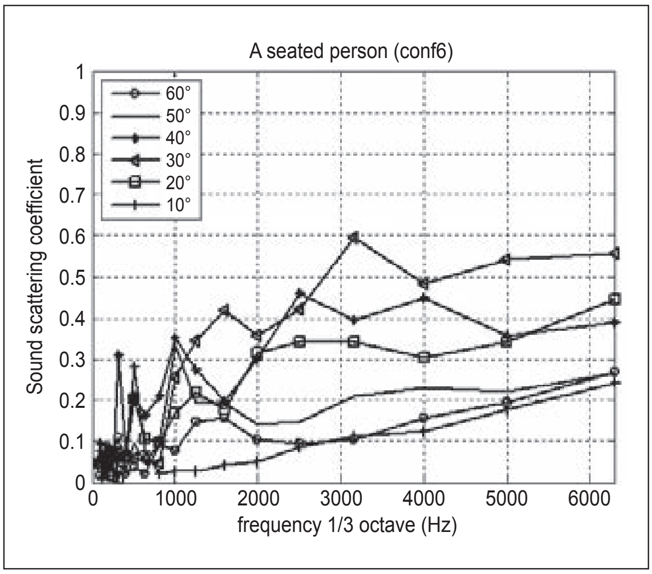

Figure 6. Sound scattering coefficient of a seated person of volume 134 × 72 × 62 cm³.

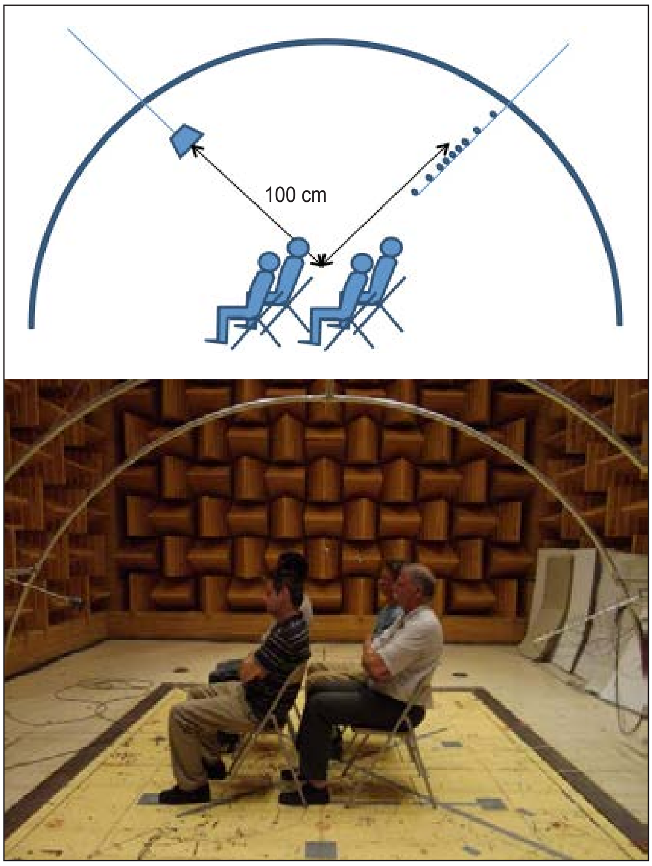

Figure 7. Experimental set-up for measuring the sound scattering coefficient of four people.

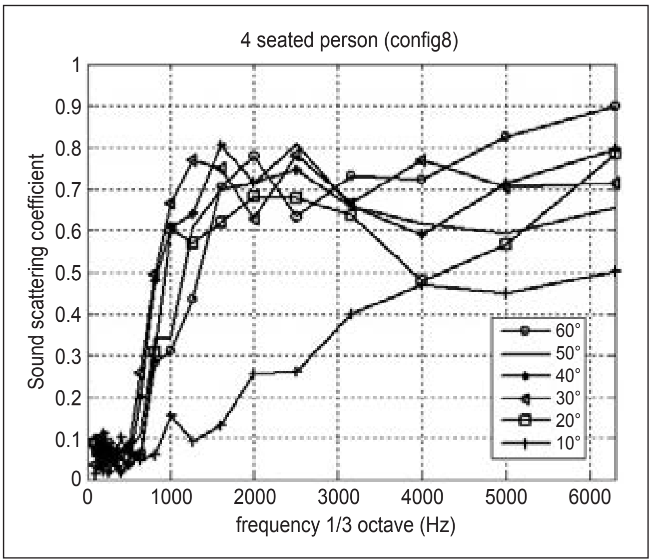

Figure 8. *Sound scattering coefficient of four people.*

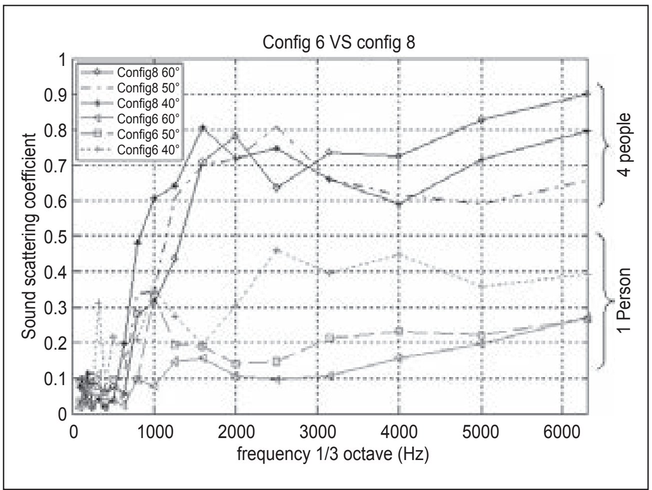

Figure 9. *Comparison between the sound scattering coefficient of one person and that of four people.*

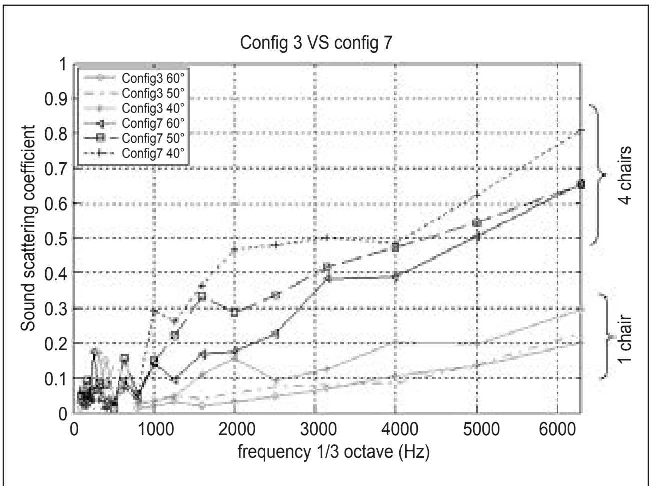

Figure10. *Comparison between the sound scattering coefficient of one chair and that of four chairs.*

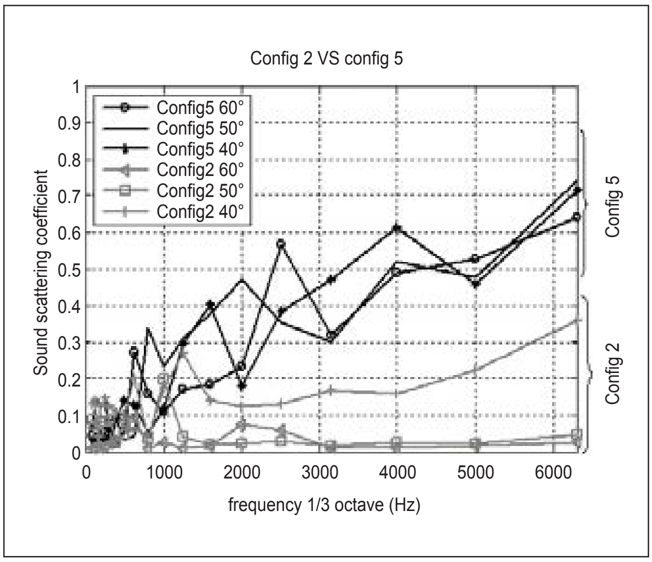

Figure 11. *Comparison between the sound scattering coefficient of a table and that of a table + three chairs + a computer.*

the surfaces, hence causing more scattering. The scattering coefficient almost doubled with a larger number of people. We obtained the same results when measuring the scattering coefficient above a chair and comparing it with that of four chairs (Figure 10) or three chairs + a table + a computer (Figure 11).

4. SOUND SCATTERING COEFFICIENT DATABASE

The set of these measurements led to establishing a global list of scattering coefficients of objects and people inside industrial workplaces by one-third octave bands (Table 1).

In this table, we have deliberately presented the values by category. Indeed, during the measurement campaign we observed that for the same structure studied, the results could fluctuate slightly with a standard deviation around 0.05. The asterisks in the table correspond to scattering coefficient values lower than 0.05.

The sound scattering coefficient increased as a function of the type of uneven surface and frequency. Below 500 Hz, the scattering coefficient was low for this category of volumes studied (people, chairs, tables, cabinets). The greater part of the reflected sound pressure was specular, for example in the case of the table and cabinet. However, above 1 kHz, the scattering coefficient became higher. This confirmed that scattering increased, on the one hand with frequency, and on the other when the structure had a more complex uneven surface, for example with the configuration of a table + three chairs.

Table 1. *Sound scattering coefficient of the scattering structures studied.*

	A cabinet	a table	a chair	table + 3 chairs	table + 3 chairs + PC	a person	4 chairs	4 people
Freq.	config1	config2	config3	config4	config5	config6	config7	config8
100	*	*	*	*	*	*	*	*
125	*	*	*	*	*	*	*	*
160	*	*	*	*	*	*	*	*
200	*	*	*	*	*	*	*	*
250	*	*	*	*	*	*	*	*
315	*	*	*	0.1	0.1	0.2	0.2	0.3
400	*	*	*	0.1	0.1	0.15	0.10	0.3
500	*	*	*	0.1	0.2	0.20	0.2	0.4
630	0.1	0.20	0.1	0.1	0.15	0.15	0.20	0.45
800	0.08	0.5	0.05	0.1	0.1	0.15	0.2	0.4
1000	0.05	0.5	0.05	0.1	0.1	0.21	0.1	0.4
1250	0.05	0.15	0.01	0.15	0.2	0.20	0.15	0.4
1600	0.1	0.11	0.1	0.15	0.2	0.2	0.2	0.50
2000	0.1	0.1	0.15	0.1	0.2	0.2	0.2	0.5
2500	0.1	0.1	0.15	0.1	0.20	0.25	0.2	0.55
3150	0.1	0.1	0.15	0.15	0.2	0.25	0.25	0.5
4000	0.15	0.1	0.2	0.15	0.3	0.25	0.25	0.45
5000	0.15	0.15	0.2	0.1	0.35	0.25	0.3	0.5
6300	0.25	0.25	0.3	0.3	0.4	0.3	0.4	0.55

5. CONCLUSION

The aim of this work was to present a list of sound scattering coefficients for structures having uneven surfaces found in industrial work places (furniture, people present inside them).

The series of measurements was performed in situ using a portable system obtain the sound scattering coefficients of uneven structures in industrial workplaces. This portable system based on the method developed by Vorländer and Mommertz was adapted to the reverberating conditions of industrial workplaces by using a directive acoustic antenna and an impulsive source already used for measuring acoustic absorption.

The measurements were performed in a semi-anechoic chamber at the INRS with a set-up dedicated to industrial workplaces. This was done in view to using the same set-up in future measurement campaigns on the site. As expected, these measurements led to observing:

– scattering that increased when the unevenness of the surface became more complex,
– low scattering from furniture with large flat surfaces such as cabinets,
– increasingly high scattering with frequency whatever the structure with an uneven surface studied,
– higher scattering with normal incidence, and lower scattering with grazing incidence.

The global sound scattering coefficients obtained, as well as those measured as a function of the angle of incidence, will finally be incorporated in a software application used to perform preliminary acoustic field calculations at the INRS (Ray+). These coefficients provide an initial list of data useful for performing preliminary sound calculations in workplaces.

REFERENCES

[1] ONDET, A.M. and J.-L. BARBRY, Prévision des niveaux sonores dans les locaux industriels encombrés à l'aide du

logiciel d'acoustique prévisionnelle RAYSCAT, e.t.l. Cahiers de notes documentaires n°142, Editor. 1991.

[2] ONDET, A.M. and J.-L. BARBRY, Modelling of sound propagation in fitted workshops using ray tracing. Journal of the Acoustical Society of America, Vol 85, 1989, pp. 787–796.

[3] DUCOURNEAU. J, A. FAIZ, A. KHANFIR, J. CHATILLON "Measuring sound scattering coefficients of uneven surfaces in a reverberant workplace – Principle and validation of the method" Applied acoustics Vol 74, 2013, pp 653-660.

[4] DUCOURNEAU J., FAIZ A. CHATILLON J.,– New device for measuring mapping of sound scattering coefficients of vertical uneven surfaces in a reverberant in a reverberant workplace, Applied Acoustics, Vol 90, 2015, pp 21–30.

[5] VORLANDER, M. and E. MOMMERTZ, Definition and measurement of random-incidence scattering coefficient,. Applied Acoustics, Vol 60, 2000, pp 187 – 199.

[6] DUCOURNEAU, J., A. FAIZ, and J. CHATILLON. Measurement of sound diffusion coefficients of a sinusoidal surface in a reverberant workshop, InterNoise 2010, Lisbonne Portugal.

[7] DUCOURNEAU, J., V. PLANEAU, and A. NEJADE, Design of a multipolar weighting for acoustic antennae. Applied Acoustics, Vol: 70, 2009, pp 484–492.

An empirical method for prediction of tram noise

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ABSTRACT

An empirical method for prediction of tram noise has been developed based on an environmental noise monitoring program for Oslo's trams. The model is designed to predict noise from individual tram passages. A multivariate regression has been performed based on measurements of acoustical and other parameters for 960 tram passages during 5 years. The estimated SEL and MAX, A-weighted levels from the overall regression have been compared to the measured levels from each passage. Three other investigations have also been made based on the data collected. The first one is an analysis of whether the measurement point has an effect beyond the parameters included in the overall analysis. The second one is an analysis of whether there was any difference between vehicles of the same series. The third one is a control of trams with special spectra against the maintenance records.

1. INTRODUCTION

The trend towards denser and bigger urban areas on the one hand and the desire to avoid modes of transport using fossile fuel on the other will increase the demand for electrically powered mass transport like trams. This leads to more people being exposed to noise from trams, but good results with quiet trams have been reported [1].

The noise monitoring program for the trams of Oslo was originally started in 2007 as part of ISO 14000 certification for Sporveien, the publicly owned company that runs the trams and metros of Oslo. Initially in 2007 the measurements were made in 8 points with at least 10 tram passages in each of the points. The program was designed to uncover longterm trends in the noise emission from the trams of Oslo through yearly measurements. Later, in 2010, the measurements of rail quality were introduced. In 2012 the first prediction method for SEL and MAX, A-weighted sound level from individual tram passages, was presented [2]. There are two main types of tram in Oslo. There are 40 of the older type SL-79, and 32 of the more recent type SL-95.

Different types of track would be expected to results in different noise emission [3]. There are three types of track in Oslo:

- Rails embedded in city streets
- Ordinary ballast track
- "Green track", which is a concrete structure carrying the rails with soil and grass between the rails.

As the data set accumulated over the years, it was decided to investigate whether it could be used for more than an evaluation of a trend in noise emission from Oslo's trams. This article deals with the development of an empirical model for tram noise based on the data set already collected.

Section 2 gives a description of the measurements, how they were performed and which data were collected. Section 3 gives a description of the analysis methods applied for overall statistics. Section 4 gives a description of other types of more detailed analysis. Two types of detailed analysis were made on the A-weighted levels. The first one was made in order to investigate whether some of the measurement points gave different results than would be expected from the overall analysis. The other one was made in order to investigate whether there were especially noisy or especially quiet trams. Finally an investigation was made of whether trams that had a deviant spectrum had a mechanical problem on the given day the noise from it was measured. Section 5 gives a description of the results of comparing the estimated noise from trams with the actually measured values. In Section 6 follows a discussion of results, while finally Section 7 gives suggestions for further research.

2. METHOD OF MEASUREMENT

The method consists of noting all parameters expected to be relevant for the measurements [4]. The measurement series has been repeated every autumn since 2007. A total of 16 points have been used during the years and included in the overall analysis. Table 1 shows a list of the points and the years in which measurements have been made in each point. In each point a series of measurements are made on one day per year. For each day at least 10 tram passages have been measured. The data acquired could be put into three groups:

- Acoustical parameters
- Non – acoustical parameters
- Rail surface corrugation

This information is required in order to develop an empirical model for noise from trams.

2.1. Acoustical parameters

For each passage of a tram the following parameters are noted:

- SEL, A-weighted and in 1/3-oktave bands
- $L_{A(F)max}$ and $L_{(F)max}$ in 1/3-oktave bands

Table 2 shows an example of a part of a measurement log as recorded.

2.2. Non-acoustical parameters

For every site the local geometry is measured once for the site, see figure 1 for an example of the documentation. Most of the immission points have been used every year. Some points have been changed over the years, or they have been suspended for a year or two during construction works on or close to the track. Table 1 gives an overview of the points used each year. In the present article the vertical gradient of the track has been included in our analysis in addition to the parameters previously reported [2].

Every measurement day on a given site the non-acoustical parameters have been noted as follows:

- Weather conditions are noted, temperature, wind speed and wind direction. The measurements are made at close distances, so that the meteorological conditions have minimal influence on the results. It is noted whether background noise is a potential problem.
- For each tram passage the identity of the tram is noted. The identity of the tram is marked with a

Table 1. Measurement points.

#	Point	2010	2011	2012	2013	2014
1	Toftes gate	X	–	–	X	X
2	Grensen	X	–	–	–	–
3	Drammensveien 53	–	X	X	X	X
4	Cort Adelers gate 17	X	X	–	–	–
5	Kirkeveien at Frognerparken	X	X	X	X	X
6	Lilleakerbanen at Hoff	X	X	X	X	X
7	Grefsenplatået	X	X	X	X	X
8	Kirkeveien at Arboes gt	X	X	–	–	–
9	Nygata	X	X	–	–	–
10	Storgata 36 B	X	X	X	X	X
14	Nils Henrik Abels vei	X	–	–	–	–
15	Abbediengveien 5	X	–	–	–	–
16	Thorvald Meyers gt	X	X	–	–	–
17	Forskningsparken	–	X	X	X	X
20	Ekebergbanen	–	–	X	X	X
21	Grefsenveien at Brettevilles gate	–	–	–	–	X

Table 2. Example of part of measurement log.

		2014		
Measurement date		27.oct.14		
Temperature:		13	°C	
Wind speed		1,5	m/s	
Wind direction		-		
Background noise		-	dBA	
Vehicle type/Id #	**Direction**	**Vehicle speed (km/h)**	**LAF(max) (dB)**	**SEL (dB)**
79/108	Inbound	37	90	93
79/125	Inbound	26	87	91
79/127	Inbound	28	84	89
79/120	Inbound	28	86	90
79/116	Inbound	23	85	89
79/136	Inbound	35	88	92
79/124	Inbound	31	88	91
79/126	Inbound	35	85	89
79/119	Inbound	27	84	89
95/152	Inbound	28	85	91
95/161	Inbound	26	84	90
95/144	Inbound	35	89	94
Average				
SL 79		30	87	91
SL 95		30	87	92

three-digit number clearly marked in front, in the rear and on both sides of the tram. The trams of Oslo are of two main types, SL-79 and SL-95 [5]. Table 3 shows the main technical data of each type of tram.

– Vehicle speed is usually measured with a laser.
– The direction of the tram is noted. By convention "inbound" means towards Oslo city centre, "outbound" means away from city centre. Special noteworthy details from each measurement are also noted.

2.3. Rail corrugation measurements

Since 2010 measurements of rail corrugation were included in the noise monitoring program. These measurements have been made according to ISO3095-2005 [6]. Figure 2 shows an example of the measurements of the rail corrugation. Rail corrugation measurements are made with an ATP-RSA for both rails in both directions past the measurement point. The idea that rail corrugation has an influence on noise from rails and wheels is not new. One author states that: "The roughness of the rail is the main source of the noise emission of the tramcar" [7]. A more recent source talking about the effect of rail grindings on railways indicates that the effect is much more pronounced on new and modern rolling stock than on older vehicles [8]. The instrument used for the measurement is suitable for this type of measurement [9]. Danish railway authorities use rail corrugation measurements for maintenance programs as well as for noise control [10].

Table 3. Main technical properties of SL-79 and SL-95.

Property	SL-79	SL-95
Length	22,4 m	33,1 m
Width	2,6 m	2,5 m
Bogie wheel distance	1,8 m	1,8 m
Wheel diameter	680 mm	680 mm
Weight empty	32,8 tonnes	65,0 tonnes
Highest speed	80 km/h	80 km/h
Seats	71	88
Room for standing persons	66	108
Year built	1982-83 & 1989-90	1998-2000

3. METHOD OF ANALYSIS

The analysis of the results has been divided into three parts:

– A main overall analysis using linear regression with 8 predictors onto two different outcome parameters, SEL A and $L_{A(F)max}$.
– Factor analysis to determine: a) whether the individual measurement point gave any significant contribution beyond that predicted by the overall analysis and b) whether each individual tram gave any significant contribution beyond that predicted by the overall analysis.
– Spectrum analysis from each measurement day to see whether there was an anomaly in the noise from any individual tram.

The main overall analysis is described in section 3.1. The other types of analysis are described in section 4.

3.1. Main overall analysis

The parameters, the method of acquisition and the representation in the statistical analysis of parameters are shown in table 4. The principle of the regression is to find the contributing factors to the noise measured. The

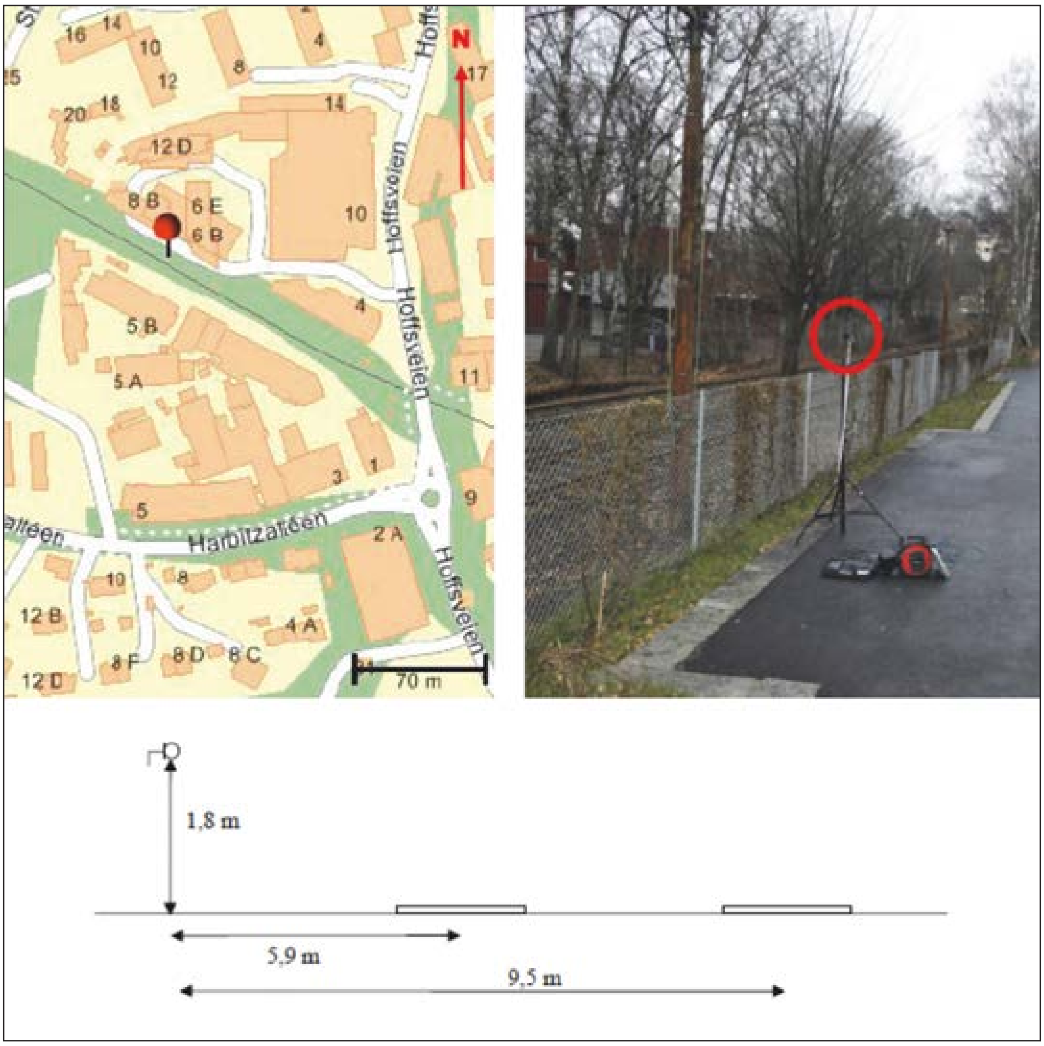

Figure 1. Example of data sheet for measurement point.

Figure 2. Example of field measurement of rail corrugation.

noise level as SEL or MAX, A-weighted, free field, has been defined as an outcome. Other factors have been defined as predictors of the noise. Some of the predictors have been transformed before the run of the regression as described in the following text and in table 4. The assumption has been that the following parameters contribute to the noise level actually measured:

- **Speed of the vehicle,** represented as the base 10 logarithm of the measured speed in km/h. The speed has usually been measured with a laser, and care has been taken to ensure that the speed is measured as the tram is on its way past the microphone. Drivers have been instructed to drive as they would normally do during our measurements. The range of speeds have been between 10 and 70 km/h. The regression factor is termed p_v.
- **Distance** from the track centerline to the microphone. This parameter is only measured once for each measurement point. The distance is represented in the regression by the base 10 logarithm of the distance in meters. The range of distances in the

Table 4. Factors included in overall statistical analysis.

Predictor /factor	Data gathered	Used in analysis after data reduction/ conditioning
Speed (km/h)	Measured with laser	Log_{10} (speed) past the mic
Distance (m)	Distance from track to microphone	Log_{10} (distance)
Year measured	Date	Year, two digits
Tram type (SL 79/SL 95)	Vehicle # (72 trams)	Vehicle type (two types)
Track type	Three types	0,1,2
Rail quality, given as equivalent corrugation spectrum in dB rel. 1 μm	≈ 100 parameters per rail	One number per track
Time since grinding	Number of years	Number of years
Gradient	Approximate vertical height difference per traversed meter horizontally	Gradient in ‰
Outcome / response		
Noise	≈ 60 parameters per passage of vehicle	Single number rating, corrected for influence of buildings, in SEL or MAX A-weighted

measurements presented is 2 to 13 meters. The regression factor is termed p_d.

- The year has been entered as a two-digit number omitting the preceding 2-0. The regression factor is termed p_y.
- Tram type has been entered as 0 for SL95, 1 for SL79. With only two alternatives a linear regression is equivalent to a factor analysis. The regression factor is termed p_s.
- Track type has been entered as 0 for city street, 1 for ballast track and 2 for green track. It was originally assumed that the green track would be the quietest and the city street would be the noisiest. The regression factor is termed p_t.
- **Rail quality** has been entered as the single number rating for the most corrugated one of the two rails on a track. The value ranges from around 15 for the best new track to over 30 for the most worn tracks investigated. The regression factor is termed p_c.
- **Time since grinding** has been entered as an integer number of years since the last grinding, this is normally in the range 0 to 5. Some tracks were ground during the summer before the autumn measurements, sometimes the track was new. For lines with little traffic there may be a 5 year interval between grindings. The regression factor is termed p_g.
- **Gradient** is given in ‰ average vertical height difference per unit of horizontally traversed distance during the measurements. The number ranges from 0, flat, to 75, the steepest descent investigated. The regression factor is termed p_h.

Noise is given as SEL and MAX, FAST, free field, for each immission point. The correction for reflections from building facades has been entered as 3 dB if there are buildings on one side of the track, 6 dB if there are buildings on both sides of the track.

The main analysis of the contribution of each predictor has been performed for both SELA and MAX, FAST AS for three cases:

- All measurements
- All measurements with vehicle speed ≤ 30 km/h
- All measurements with vehicle speed ≥ 30 km/h

Noise from railbound traffic is dominated by different sources at different speeds. There is a minimum noise at standstill, and the contribution of this basic noise is reduced as rolling noise takes over at increasing speed. This means it seems reasonable to split the analysis between different speed ranges. The choice of 30 km/h as a dividing line is made because this is an established convention in the Oslo area. For the Oslo metro, different parameters are already used for noise calculations at speed above 30 km/h and below 30 km/h. It is also part of the consideration that the speed limit for road traffic in purely residential areas in Oslo is often 30 km/h, which is the kind of area where the tram would be expected to be a problem at short range.

The measurement points as distinct entities are not directly included in the overall analysis, only the distance and the parameters of the track (track type, rail corrugation and years since last grind). The overall analysis does not include detailed investigation of the spectrum.

The use of a continuous variable for tram type is not problematic. As long as there are only two distinct values, a linear regression using a continuous variable is equivalent to defining it as a categorical variable. For the track type, however, the situation is a bit more problematic. It seemed natural to assume that city street would be the noisiest type of track, green track the quietest with the ballast track somewhere in the middle. Investigations into this problem using different type of analysis have given inconclusive results. One possible reason is that there are no measurement points with green track where both types of tram run. This may lead to confounding of the results.

4. OTHER ANALYSIS

4.1. Factor analysis

The term factor analysis is used about further analysis focusing on a smaller detail of the overall picture. This type of statistical analysis has been made in order to look for explanations to the uncertainties in the overall analysis. Two possible contributors have been singled out for investigations: measurement points and the individual trams.

4.1.1. Measurement point

This analysis was made in order to investigate whether the measurement points had some distinct influence beyond that included in the parameters given above. This was done by including the measurement point as a categorical variable (called factor in the statistics program R) in the overall regression analysis.

4.1.2. Tram identity

There are only 72 trams in Oslo, and there have been measured 960 passages. All the trams have been measured more than once, some vehicles more than 30 times. This means that running the statistical analysis with the tram identity as a categorical variable (called factor in the statistics program R) might reveal more new information as to whether there is a difference between the vehicles.

4.2. Detail analysis of individual measurement series 2012

It was decided in 2012 to investigate whether there was any clear connection between the spectrum of particularly noisy trams and the state of maintenance. Spectrum analysis has not been included in the overall analysis. The spectrum analysis has been performed for each individual measurement point individually. The purpose of this analysis was to see whether there was any way to reduce noise complaints by adjusting maintenance routines. For each measurement day in a given point the average spectrum was plotted together with the spectrum for particularly noise vehicles. The results were checked against the maintenance records of the trams. Roughly half the cases of a special spectrum could be explained by the maintenance records. One case is shown in figure 3, another in figure 4. The case in figure 3 was found to be due to a leak in a hydraulic system on that measurement day, leading to a compressor running continuously on tram # 101. This compressor normally runs at short intervals only. And thus this tram emitted much more high frequency noise on that day than the other trams operating on that line. The case in figure 4 was not explained by the maintenance records. However the driver complained about noise while braking, so something was most likely wrong with the vehicle.

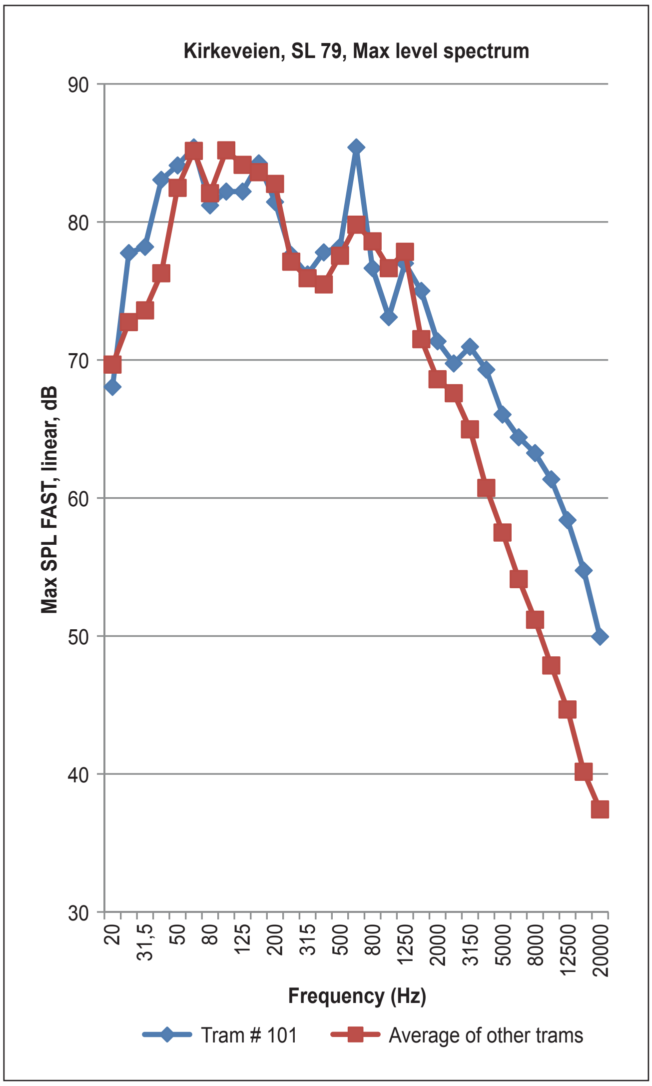

Figure 3. Example of a noisy tram.

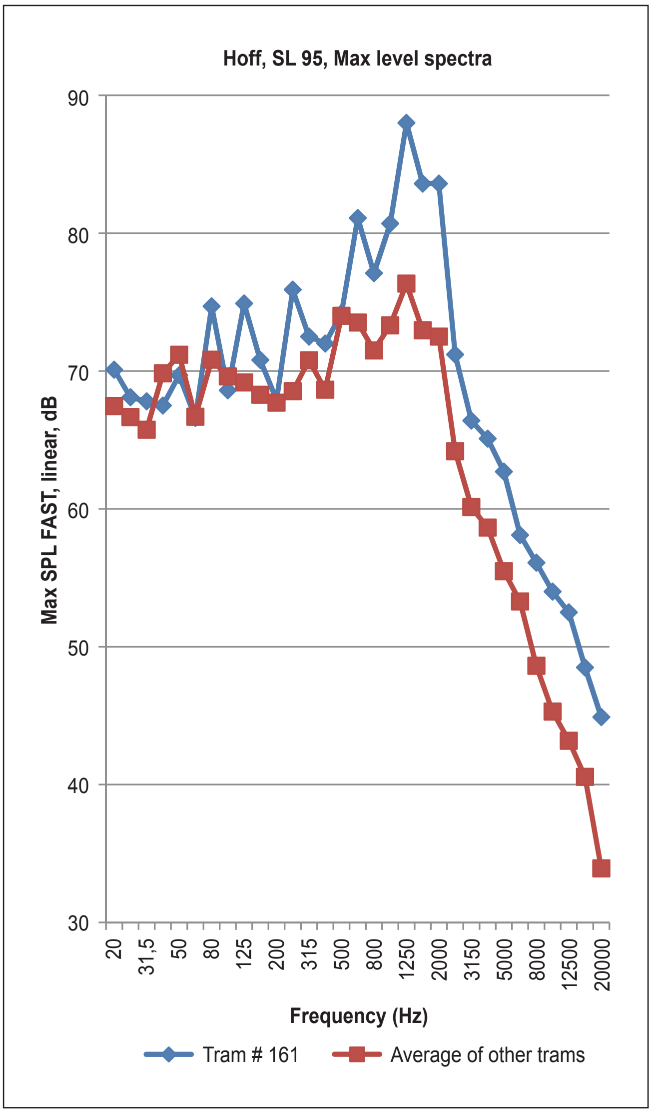

Figure 4. Example of a noisy tram.

In 2013 a similar type of analysis yielded no results. No special spectra were found that could be matched with the maintenance data base. A probable explanation could be that the noisy events found in 2012 changed the attitude of the people working in maintenance at the tram garage, so that the trams were generally kept in a better state.

5. DEVELOPMENT OF EMPIRICAL PREDICTION METHOD

The concept of developing a prediction method based on field measurements only is not new [11]. This is an alternative to developing theoretical models especially suited for trams [12, 13]. The main purpose of the present article is to show the results of developing a local empirical prediction method. The resulting formula for the estimated noise level is as follows:

$$L = L_0 + p_v(\log(10)\text{speed}) + p_d(\log(10)\text{distance}) + \\ + p_y\ {}^*\text{year} + p_s\ {}^*\text{tram type} + p_t\ {}^*\text{track type} + \\ + p_c\ {}^*\text{rail quality} + p_g\ {}^*\text{time since grinding} + p_h\ {}^*\text{gradient}$$

Where:

- L_0 is the estimated intercept from the regression analysis
- P_v is the regression factor for the log (base 10) of the tram sped
- P_d is the regression factor for the log (base 10) of the distance from the track to the microphone
- P_y is the regression factor for the year the measurement was made
- P_s is the regression factor for the tram type
- P_t is the regression factor for the track type
- P_c is the regression factor for the rail quality given as corrugation in dB rel. 1 µm
- P_g is the regression factor for the time since last grinding of the track
- P_h is the regression factor for the vertical gradient

The other parameters have been described in detail in section 3.1.

It should be noted that the model actually predicts the noise from each individual tram passage. The accuracy to be expected from a calculation of an aggregated level like L_{den} or $L_{eq,24h}$ should be much better than the accuracy for an individual passage of trams. The same goes for the prediction of $L_{5AF,}$ which is meant to be the expected second highest maximal level from 20 passages of trams.

The development of a method consisted in finding which parameters to include in the regression model. In principle this can be done by including more parameters in the regression as long as the r^2 continues to increase [2]. These first attempts at a regression used the first 7 parameters described in section 3.1: Speed, distance, tram type, corrugation, year of measurement, track type and time since grinding. Later the vertical gradient has also been included, as this has been shown to be of importance in the development of an empirical prediction method for another city, Kosiçe, Slovakia [11].

The results from the regressions at speeds up to 30 km/h and at speeds from 30 km/h upwards were compared with the actually measured noise level in each individual case for both SEL A and $L_{A(F)max}$. The residue has been plotted for each tram passage. The residue is defined as measured level minus estimated level.

6. RESULTS AND DISCUSSION

The results of the analysis are discussed below. The results are divided into overall linear regression, factor analysis and empirical prediction.

6.1. Overall linear regression

The results of the overall linear regression are shown in table 5. The regression factors have been calculated for all the 6 investigated cases from section 3.1, SEL and MAX, A , FAST. Some characteristics of the regression coefficients are reasonable. For both SEL and MAX the overall correlation is higher at speeds from 30 km/h upwards than at lower speeds. The speed dependence is steeper at higher speeds. This agrees with intuition, since some noise from the tram is present even at standstill. The faster the tram goes, the smaller the contribution of noise from machinery that is independent of driving speed becomes. The distance attenuation is essentially the same independent of speed. Distance attenuation will not necessarily be attributable to a line source or point source, since all the measurements have been made at a distance shorter than the greatest dimensions of the tram. The greatest measurement distance is 13 meters, and the smallest of the trams has a length of 22 meters. This is a limitation regarding the theoretical description of the sound field, since all measurements have been made in the near field of the source. It also seems clear that the difference in noise between the two types of tram is greater at higher speeds.

There is a theoretical problem in running the analysis on MAX, A –weighted level. Normally with railbound noise sources like trams the maximal levels in different frequency ranges will occur at different times. For example noise from braking or curve squeal could easily come at different times than noise from bogie resonances. This means that the maximal A-weighted level is usually slightly lower than the A-weighted sum of maximal 1/3-octave band levels. In our as yet unpublished experience this discrepancy usually amounts to 2-3 dB.

6.2. Factor analysis

The results of the two types of factor analysis made on the whole data set will be described below.

6.2.1. Measurement points

The factor analysis of measurement points showed that some of the measurement points had a statistically significant effect on the noise beyond that which could be explained by the overall statistical analysis. The presented difference is the difference left after correction for all other parameters that change from immision point to immision point, distance, track type, rail corrugation and gradient. A full printout of these results is shown in table 6. Points 7 and 9 are slightly noisier than the others, points 5, 6 and 10 are slightly quieter. Further investigation will include horizontal curvature in the statistical analysis which may help to explain these local differences .

6.2.2. Individual vehicles

There are 960 passages of 72 vehicles included in the database of this investigation. It was decided to look for whether any of the trams were particularly quiet or noise even when corrected for all other factors included in the analysis. Factor analysis using the tram identity gave as a result that the trams 110, 131, 132 and 138 have been

Table 5. Regression coefficients.

PARAMETER	SEL A – regression factors			MAX A – regression factors		
	All	Up to 30 km/h	30 km/h and faster	All	Up to 30 km/h	30 km/h and faster
Intercept, p_0	67,187077	76,538546	59,461542	60,235397	73,359345	50,80419
Logspeed, p_v	13,310782	8,929057	15,318161	18,415826	12,124811	20,926071
Logdist, p_d	–4,79454	–4,661183	–4,218583	–7,091294	–6,303489	–6,645283
Year, p_y	–0,037599	–0,283036	0,253725	–0,067452	–0,410346	0,28885
Train, p_s	–2,262893	–1,510515	–2,973198	–2,559884	–1,22345	–3,640547
Track, p_t	0,76528	0,84514	0,690741	0,830644	0,911343	0,78178
RSA, p_c	0,144813	0,099541	0,198706	0,050191	–0,022064	0,119541
Lastgrind, p_g	–0,372942	–0,11018	–0,614146	–0,494909	–0,234422	–0,744633
Gradient, p_h	0,015315	0,019999	0,015661	0,021583	0,029522	0,0207036
Correlation						
r^2	0,531	0,4241	0,4663	0,5708	0,3935	0,5234

Table 6. Estimated influence of the measurement point.

	Estimate	Std. Error	t value	Pr(>|t|)	
MP(MP01)	0.10710	0.55643	0.192	0.847413	
MP(MP02)	0.06366	0.82141	0.078	0.938240	
MP(MP03)	-0.16124	0.60002	-0.269	0.788201	
MP(MP04)	-1.11884	0.71385	-1.567	0.117376	
MP(MP05)	-2.64880	0.64395	-4.113	4.24e-05	***
MP(MP06)	-2.46146	0.50404	-4.883	1.23e-06	***
MP(MP07)	1.85212	0.50156	3.693	0.000235	***
MP(MP08)	-1.25658	1.07513	-1.169	0.242796	
MP(MP09)	2.95450	0.81764	3.613	0.000318	***
MP(MP10)	-1.34858	0.38285	-3.522	0.000448	***
MP(MP14)	1.60001	1.10588	1.447	0.148281	
MP(MP15)	-1.80250	1.00982	-1.785	0.074589	.
MP(MP16)	-0.89565	0.71667	-1.250	0.211707	
MP(MP17)	1.03587	0.53955	1.920	0.055177	.
MP(MP20)	1.08895	0.61228	1.779	0.075644	.
MP(MP21)	2.99	Not yet valid data			

quieter than predicted from the overall analysis. Trams 153, 163, 164 and 166 have been noisier. All the apparently quiet trams are of the SL-79 series, and all the apparently noisy trams are of the SL-95 series. A possible explanation is that the SL-95 series is generally of a poorer mechanical quality than the SL-79 series, even though the trams of the SL-79 series are older.

6.3. Empirical prediction

One possible way of determining the practical applicability of the work is determined by how well the models actually can predict noise from an individual tram passing. In figure 5 through 8 are shown the differences between the estimated and measured level for each passing tram. The estimate is based on the overall regression for the 4 selected subcases:

– Measured vs. estimated noise – SEL A, v ≤ 30 km/h, shown in figure 5
– Measured vs. estimated noise – SEL A, v ≥ 30 km/h, shown in figure 6
– Measured vs. estimated noise – MAX A, v ≤ 30 km/h, shown in figure 7
– Measured vs. estimated noise – MAX A, v ≥ 30 km/h, shown in figure 8

The figures show that the estimated level lies within ± 5 dB for about 85% of the individual passages. The

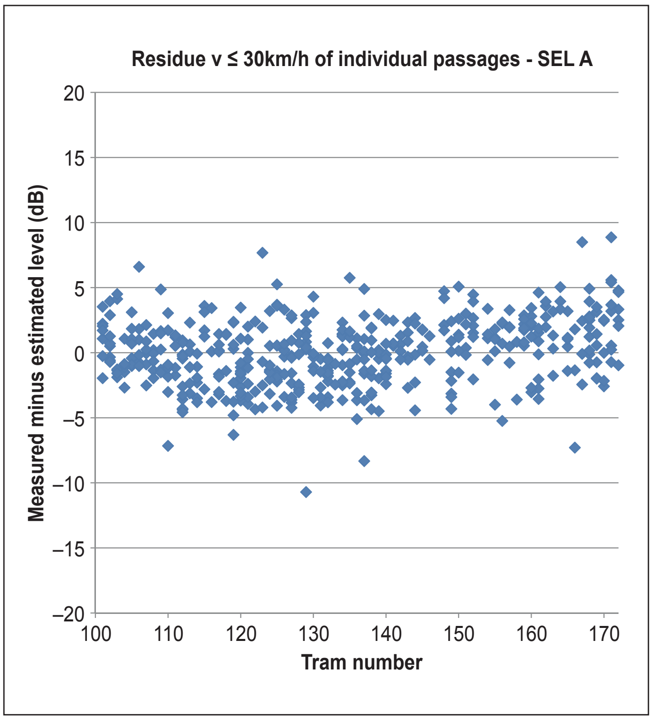

Figure 5. Measured vs. estimated noise – SEL A, v ≤ 30 km/h.

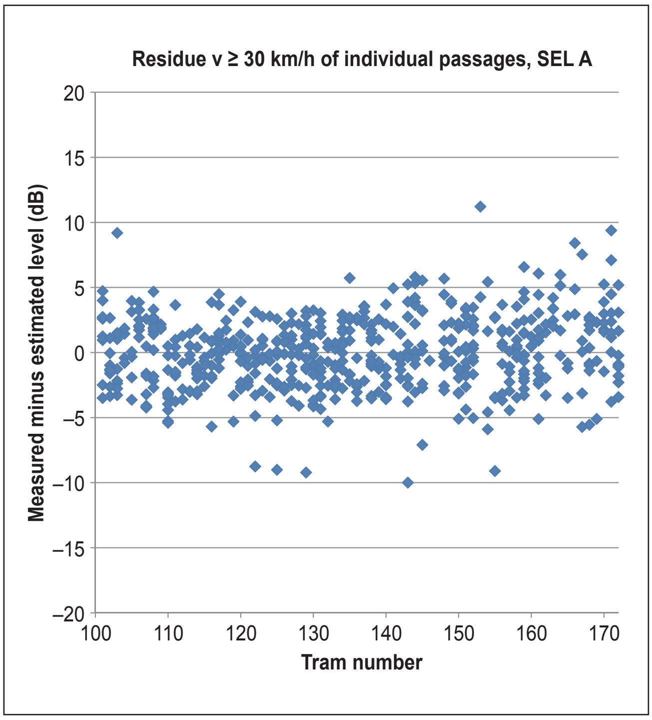

Figure 6. Measured vs. estimated noise – SEL A, v ≥ 30 km/h.

passages where the measured maximal level exceeds the estimated level by 10 dB or more are exceptional cases. This means the formulas obtained can be used for prediction of aggregate measures of equivalent levels like L_{eq} or L_{den}. They can also be used for estimates of L_{max} or L_{5AF} as long as all the parameters are inside the range that has been in use.

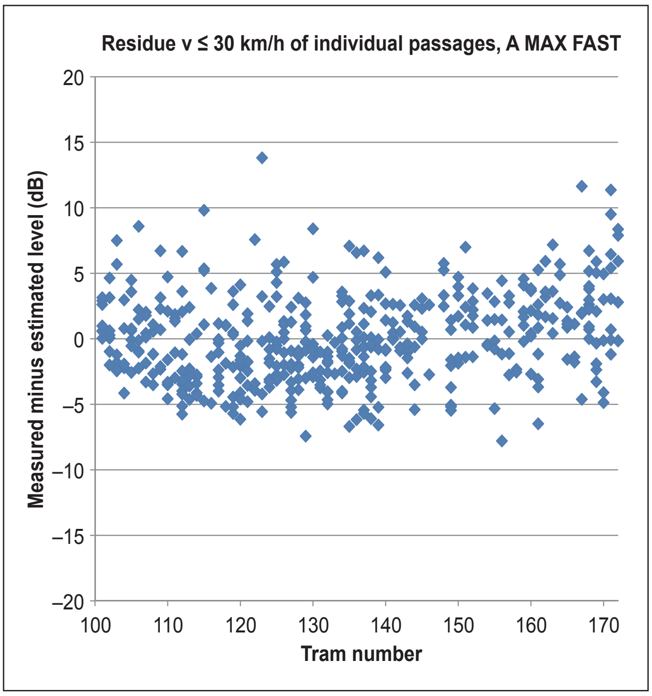

Figure 7. Measured vs. estimated noise – MAX A, v ≤ 30 km/h.

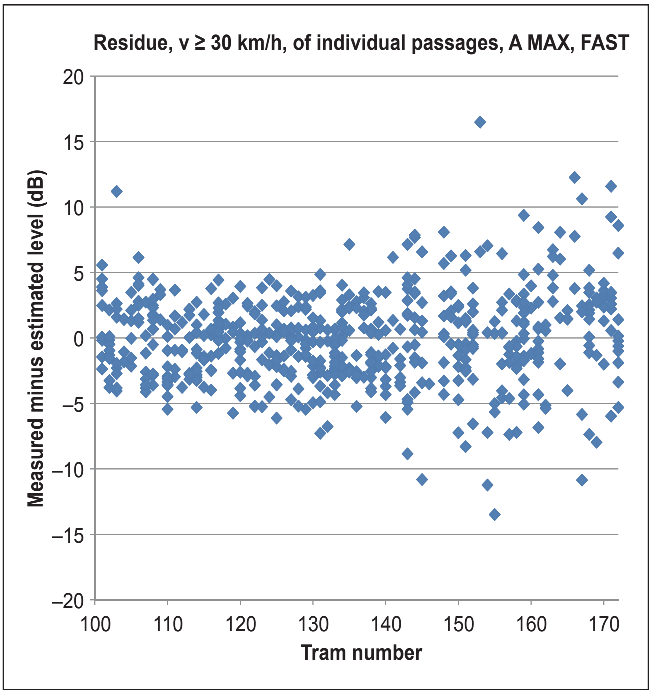

Figure 8. Measured vs. estimated noise – MAX A, v ≥ 30 km/h.

It is generally not advisable to remove especially noisy or escpecially quiet tram passages (outliers) from a multivariate statistical analysis unless there is something clearly wrong in the measurement in question. The largest difference between estimated and measured SEL is 11,2 dB. The largest difference between estimated and measured MAX is 16,5 dB. Both these are from the same passage of tram # 153, which has been identified as a noisy tram.

7. FURTHER RESEARCH

The results as given are only applicable to the trams of Oslo. However the methods described are applicable to any urban railbound transport system. It would be of great interest to try the methods in other cities. A program for noise monitoring of the metro trains of Oslo is under planning and expected to start in the spring of 2016.

8. CONCLUSIONS

An environmental noise monitoring program has been described. It has been shown that this environmental noise monitoring could be developed into an empirical model for noise prediction using multivariate statistics.

9. ACKNOWLEDGEMENTS

First of all, my sincere thanks to Sporveien, the publicly owned company that runs Oslo's metros and trams. This company has commissioned the measurements and allowed the publication of the results. In addition, Sporveien's employees Johnny Vaaga and Haagen Hølaas have taken part in the field work of the measurements. We would also like to thank Eivind Hoel, Håkan Lund and Laila Kristin Dokken Gundersen of Sporveien for the permissions to publish the results and cooperation with regards to access to the maintenance database.

Statistical analysis has been performed with the program package R, which is available for free and widely used in many fields of research. The user interface R Commander from NMBU (The Norwegian University of Bioscience, at Ås) has also been applied. This user interface is also available for free.

REFERENCES

[1] A study of the noise of Sheffield supertram - R B W Heng - Internoise 1996 Liverpool, pp. 427-432.

[2] Noise measurements on the Oslo Tram. – Atle Stensland, Tore Fodnes Killengreen, Sigmund Olafsen, proceedings Internoise 2012, New York.

[3] Noise comparison of Helsinki street car rail structures - Henrik Möller & Mats Backholm – Baltic Nordic Acoustical Meeting 1988 Tampere, pp 247-250.

[4] Målinger av støy iht. måleprogram for trikken – Måleresultater 2012, Tore Fodnes Killengreen, Sigmund Olafsen, Atle Stenslad (in Norwegian only).

Report of measurements up to and including 2012. The 2012 report was the most comprehensive one. Yearly reports have been produced every year in the range 2007-2014.

[5] Norske lok og motorvogner 1.1.2008. Norsk Jernbaneklubb, Forskningsavdelingen. A wealth of information about the rolling stock on Norwegian regular railways, museum railways, tram and metro lines up to 2008, collected by a private organization on volunteer basis, unfortunately only with Norwegian text.

[6] ISO 3095 – 2005, Railway applications -- Acoustics -- Measurement of noise emitted by railbound vehicles

[7] Noise control of tramcar noise by grinding the rails - Siegfried Riemens - Internoise 1993 Leuven, pp. 1451-1454.

[8] Rail grinding as a noise control measure - Frank Rysgaard Mortensen, Per Finne, Lars Deigaard - Internoise 2001, den Haag, pp. 147-150.

[9] Development and validation of a rail surface analyser for accurate quantification and evaluation of rail corrugation and track work acceptance after acoustic grinding - Geert Desanghere, Tom Vanhonacker - Internoise 2007.

[10] Noise and vibrations from railways depending on wheel/rail conditions - S. Junge, J.T. Christensen, I. Brinchmann – Baltic Nordic Acoustical Meeting 1994 Aarhus, pp. 357-362.

[11] Prediction of noise from trams - Ján Mandula, Brigita Salaiová, Mária Koval'akova´ - Applied Acoustics 63(4), 2002, pp. 373-389.

[12] Noise emitted by trams- Part I – investigations on emitted noise power, vertical directivity and localization of noise sources - Joël Lelong, marie-Agnès Pallas, Roger Chatagnon – Internoise 2007, Istanbul.

[13] Noise emitted by trams – part II: development of a tram noise emission model - Marie-Agnès Pallas, Joël Legnon, Roger Chatagnan – Internoise 2007, Istanbul.

The Environmental Noise Directive at a turning point

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ABSTRACT

The burden of disease from environmental noise in Europe was recently estimated at 1.6 million healthy life years lost every year in urban areas in Western Europe. Traffic noise has been ranked second among the selected environmental stressors evaluated in terms of their public health impact. Further, the trend is that noise exposure is increasing in Europe compared to other stressors (e.g. exposure to second hand smoke, dioxins and benzene), which are declining. Noise pollution affects human health and well-being with increasing expenditures due to medical treatment and reduced productivity at work. This is translated into a societal cost which was recently estimated to 40 billion €/year in the EU (0.4% EU GDP).

In its recently adopted Environment Action Programme to 2020, the EU has envisaged to significantly decrease noise pollution within its borders, moving closer to levels recommended by the World Health Organisation, by 2020. One of the main legislative tools in achieving this aim is the Environmental Noise Directive (2002/49/EC) (END), an overarching directive aimed at achieving a common approach towards environmental noise in the EU. The European Commission is currently undertaking an evaluation of the END, and trying to assess its effectiveness and efficiency, including benefits, costs and hurdles to the implementation of an effective EU noise policy. This paper gives an overview of recent developments with regards to the END and sets the scene for a discussion on the potential developments in the years to come.

1. INTRODUCTION

The health impact of environmental noise is of increasing concern amongst the European citizens, however recent evidence shows that its reduction is still by far below the levels envisioned by European Union (EU) policy makers and legislators. In its recently adopted Environment Action Programme to 2020, 'Living well, within the limits of our planet' (7th EAP), the EU has committed itself to significantly decrease noise pollution within its borders, moving closer to levels recommended by the World Health Organisation (WHO), by 2020. One of the main legislative tools in achieving this aim is the Environmental Noise Directive (2002/49/EC) (END), an overarching directive aimed at achieving a common approach towards environmental noise in the EU. The Directive, which was adopted more than 10 years ago, has recently been further developed by agreeing common EU methods for noise assessment (revision of Annex II), which is currently followed by work on developing methods to assess the effects of noise on populations by means of dose-effect relations (revision of Annex III). At the same time, the Directive is undergoing a retrospective evaluation under the European Commission's Regulatory Fitness and Performance programme (REFIT). This paper aims to give an overview of these recent developments with regards to the END as well as set the scene for a discussion on the potential developments in the years to come.

2. THE ENVIRONMENTAL NOISE PROBLEM IN THE EU

The European Environment Agency's recently published report 'Noise in Europe 2014' demonstrates that noise pollution constitutes a major environmental health problem in Europe. The report shows that road traffic is the most dominant source of environmental noise, with an estimated 125 million people affected by noise levels greater than 55 decibels (dB) Lden (day-evening-night level), and confirming its status as the second most dangerous environmental hazard to people's health, immediately after air pollution.

At the same time, epidemiological evidence indicates that those chronically exposed to high levels of environmental noise have an increased risk of cardiovascular diseases such as myocardial infarction. Noise pollution affects human health and well-being. The health effects caused by exposure to excessive noise also impact the European economies. They put an entirely avoidable burden on health care systems which have limited resources, while at the same time generating the loss of productivity of workers whose sleep is disturbed or health affected. The burden of disease from environmental noise in Europe based on partial data was estimated by WHO-JRC and accounts for at least 1.6 million healthy life years lost every year in urban areas in Western Europe. In addition, it is estimated that environmental noise causes 30 to 50 thousand cases of premature death in Europe each year. This is translated into a societal cost which has been estimated to 40 billion euro per year in the EU (0.4% of the EU GDP).

Moreover, a full assessment is hindered by the fact that estimates on exposure to noise reported by countries are not complete, with as little as 44% of the expected amount of data being delivered in the latest reporting round of the END. Therefore the figures quoted above can be considered generally underestimated and will need to be revised as more complete data becomes available.

3. EU ENVIRONMENTAL NOISE POLICY AND REGULATORY FRAMEWORK

In its 7th EAP, the European Union committed to significantly decrease noise pollution in the Union, moving closer to levels recommended by the WHO, by 2020. The document noted that this would require, in particular, implementing an updated Union noise policy aligned with the latest scientific knowledge, and measures to reduce noise at source, and including improvements in city design. In this context, the European Commission, the Member States' public authorities and all the different stakeholders have a role to play.

The primary EU legislative tool for the assessment and management of environmental noise is the END. This Directive, introduced more than 10 years ago, aims to achieve a common European approach to avoid, prevent or reduce the effects of exposure to environmental noise harmful for health, which includes annoyance. It achieves this by requiring EU Member States to conduct a process of noise mapping and preparing action plans for noise management for all major roads, railways, airports and large agglomerations in 5-year cycles. The Directive does not set any limit values, nor does it prescribe measures to be included in the action plans. Its primary strategy for effecting improvement in noise pollution is therefore to require public authorities in Member States to collect information on noise, share that information with the public, and engage in a discussion with the public on whether and how to act on that information. The principle strategies that the Environmental Noise Directive uses are raising awareness and ensuring citizens are involved in decision-making.

Moreover, and in line with the recommendation in the 7th EAP, the END outputs provide a basis to develop EU measures to reduce noise at source. In terms of noise reduction at source, the most significant and cost-effective, long-term steps can only be taken at EU-level, as the noise sources (e.g. vehicles, airports, railway tracks) are regulated as part of the EU internal market. A number of other European legislative acts therefore address noise at source. Among these, most recently updated are the Regulation on the establishment of rules and procedures with regard to the introduction of noise-related operating restrictions at Union airports within a Balanced Approach (EU/598/2014) and the Regulation on the sound level of motor vehicles and of replacement silencing systems (EU/540/2014), both adopted on 16 April 2014. Legislation on source is complementary to the END as reducing the contribution to noise at source reduces the exposure at the receiving end.

4. REVISION OF END ANNEXES

At the time of the adoption of the END, the legislators included in the Directive an obligation for the European Commission to adapt its Annexes I, II and III to technical and scientific progress, notably to establish common noise assessment methods (Annex II) and methods for assessing harmful effects of noise by means of dose-effect relations (Annex III). The work on the former has recently been finalised, while the work on the latter is about to start.

In the period since the adoption of the END, the differing use of approaches to noise mapping has been one of the key implementation challenges recognised. The lack of comparable and common assessment methods has caused significant inconsistencies in exposure estimates, between different countries, within a single country and across the two main reporting rounds to date. A major step forward in this respect came about with the development of common noise assessment methods in Europe, the methodological framework under the name of CNOSSOS-EU. The CNOSSOS-EU became part of the EU legislative framework in the form of a revised Annex II of the END (Commission Directive (EU) 996/2015). . The new methodologies will ensure that noise in each Member State is assessed in a harmonised way, thus providing a consistent and reliable picture of the acoustic situation in the EU. The use of CNOSSOS-EU will be mandatory for all Member States after 31 December 2018, however Member States will have the possibility to transpose and start using the revised Annex II even before this date.

Furthermore, the END obliges the Commission to establish methods for assessing the harmful effects of noise by means of dose-effect relations. This will be done through the revision of Annex III of the Directive.

The Annex specifies that dose-effect relations should be used to assess the effect of noise on populations. They should concern, in particular, the relation between annoyance and Lden for road, rail and air traffic noise, and for industrial noise, and the relation between sleep disturbance and Lnight for road, rail and air traffic noise, and for industrial noise. Furthermore, if necessary, specific dose-effect relations could be presented for special situations, such as dwellings with special insulation against noise, different climates or vulnerable groups of the population. The Commission has started the preliminary work on the development of a revised Annex III by seeking the views of Member States through the Noise Regulatory Committee, and proceeded with the development of the first draft in the course of 2015. In this process, close attention will be paid to the work being undertaken by the World Health Organisation (WHO) Regional Office for Europe, which is currently in the process of producing revised Environmental Noise Guidelines for the European Region. These are expected to be published in early 2016.

5. REFIT OF THE END

In parallel with the work on fine-tuning the tools of the Environmental Noise Directive, the Directive is undergoing an evaluation in the context of the European Commission's Regulatory Fitness and Performance programme (REFIT). In view of the Commission's long-term commitment to a simple, clear, stable and predictable regulatory framework for businesses, workers and citizens, the REFIT programme aims to cut red tape, remove regulatory burdens, simplify and improve the design and quality of legislation so that the policy objectives are achieved and the benefits of EU legislation are enjoyed at lowest cost and with a minimum of administrative burden. Environmental legislation is at the centre of the exercise, with 12 REFIT intiatives, which includes the END.

The evaluation of the END, which is retrospective, will address questions such as whether the objectives of the END have been met in the most efficient and effective manner, whether the Directive is coherent with other EU legislation, whether it continues to match current needs, and whether it provides additional value as opposed to national measures alone. The evaluation will also look closely at the benefits, costs and burdens of the Directive. The process will include a thorough consultation of stakeholders through questionnaires, interviews and a dedicated workshop. Based on the work of the contractor, the European Commission will draft an evaluation report, which will also include a report on the implementation of the Directive.

The REFIT report will build on the Commission's first report on the implementation of the END from 2011, which also addressed implementation difficulties. Among the main implementation problems identified at that time were: delays in implementation by the Member States, the non-enforcement of noise limit values, the poor quality of strategic noise maps and action plans, an inconsistent use of approaches in noise mapping, divergent approaches to identify quiet areas, missing or unclear provisions of the Directive and a non-appropriate communication and involvement of the public in the noise assessment and mitigation process.

6. FUTURE PERSPECTIVES OF THE END

As shown in this paper, the EU noise policy and the END itself have come a long way since the adoption of the Directive in 2002. At the moment, the END finds itself at a turning point, with two rounds of noise mapping and action planning behind us, new common methods on noise mapping being adopted, and common approaches to assessment of health effects being discussed. It is therefore timely for it to be thoroughly evaluated under the REFIT exercise. While this exercise is foremost retrospective, it may cover some prospective issues.

7. DISCLAIMER

REFERENCES

[1] Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. OJ L 189, 18.7.2002.

[2] Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living

well, within the limits of our planet'. OJ L 354/171; 28.12.2013.

[3] WHO/JRC, 2011, Burden of disease from environmental noise, Fritschi, L., Brown, A.L., Kim, R., Schwela, D., Kephalopoulos, S. (eds), World Health Organization, Regional Office for Europe, Copenhagen, Denmark.

[4] D.J.M. Houthuijs, A.J. van Beek, W.J.R. Swart, E.E.M.M. van Kempen: Health implication of road, railway and aircraft noise in the European Union: Provisional results based on the 2nd round of noise mapping. RIVM, Bilthoven, 2014.

[5] European Environment Agency: Noise in Europe 2014. Publications Office of the European Union, Luxembourg, 2014.

[6] Regulation (EU) No 598/2014 of the European Parliament and of the Council of 16 April 2014 on the establishment of rules and procedures with regard to the introduction of noise-related operating restrictions at Union airports within a Balanced Approach and repealing Directive 2002/30/EC. OJ L 173/65; 12.6.2014.

[7] Regulation (EU) No 540/2014 of the European Parliament and of the Council of 16 April 2014 on the sound level of motor vehicles and of replacement silencing systems, and amending Directive 2007/46/EC and repealing Directive 70/157/EEC. OJ L 158/131; 27.5.2014.

[8] Communication from the Commission to the European Parliament, the Council, the European Social and Economic Committee and the Committee of the Regions: Regulatory Fitness and Performance Programme (REFIT): State of Play and Outlook. COM(2014) 368 final.

[9] Report from the Commission to the European Parliament and the Council on the implementation of the Environmental Noise Directive in accordance with Article 11 of Directive 2002/49/EC. COM(2011) 0321 final.

The members of the initial editorial board are shown in the table below. New members will be added to the board to provide expertise in topic areas not sufficiently represented by the current members of the board. It is also hoped to widen the geographical spread of the board to include members form more EAA societies.

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- promote and spread the science of acoustics, its technologies and applications, throughout Europe and the entire world
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- publish a European journal on acoustics, in printed as well as in electronic format
- organize and promote congresses, publish books and monographs, and engage in all those activities that are connected with the diffusion, promotion and development of acoustics
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• CA, Computational Acoustics • HYD, Hydroacoustics • MUS, Musical Acoustics • NOI, Noise • PPA, Psychological and Physiological Acoustics • RBA, Room and Building Acoustics • ULT, Ultrasound

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Acta Acustica united with Acustica is an international, peer-reviewed journal on acoustics. It is the journal of the

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SCHOLA
Product manager: *Malte Kob*
Schola is an online platform for education in acoustics in Europe: https://www.euracoustics.org/activities/schola. Through Fenestra, it offers information on university acoustics courses in Europe at different levels (Bachelor, Master, Ph.D.).

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This new technical journal will be written by practitioners for practitioners and other professions: a new link between all members of all EAA societies. The journal will be published four times a year in electronic form only.

YAN - YOUNG ACOUSTICIANS NETWORK
Contact person: *Cristina Zamorano*
This network is a non-profit initiative within the European Acoustics Association (EAA) with the primary goal is to establish acommunity for young researchers and young professionals in the field of Acoustics; to connect them and to provide support. It organises events at conferences and provide services that contribute to the community, such as a monthly newsletter and many communication channels to enable networking.

FORUM ACUSTICUM
Forum Acusticum is the triennial international convention organised by a national acoustical society on behalf of EAA. It is, in effect, a forum comprising a variety of different activities: high-quality scientific congress with invited plenary lectures, structured sessions, invited and contributed papers, an exhibition that includes commercial firms, laboratories and agencies, social meetings of acousticians with receptions, visits and awards.

EURONOISE
Euronoise is the European Conference and Exhibition on Noise Control, coordinated by the EAA Technical Committee Noise and organised by a national acoustical society on behalf of EAA.

EUROREGIO
Euroregio is an expression of EAA support for traditional regional events organized by groups of countries. Where and when appropriate, the regional events can be extended towards a full European and international scale.

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EAA supports with grants and best paper and presentation awards the active participation of students and young researchers at EAA major events (Forum Acusticum, Euronoise, Euroregio).

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